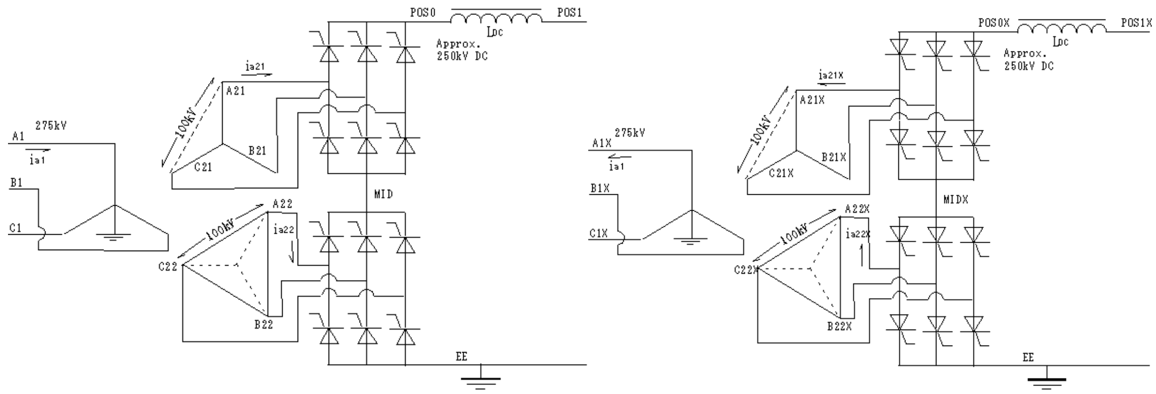
9. Typical power electronics circuits in power systems

More and more power electronics technologies have been widely applied to power systems. In the chapter, several typical and primitive circuits are surveyed regarding the functions.

9.1 HVDC converter/inverter

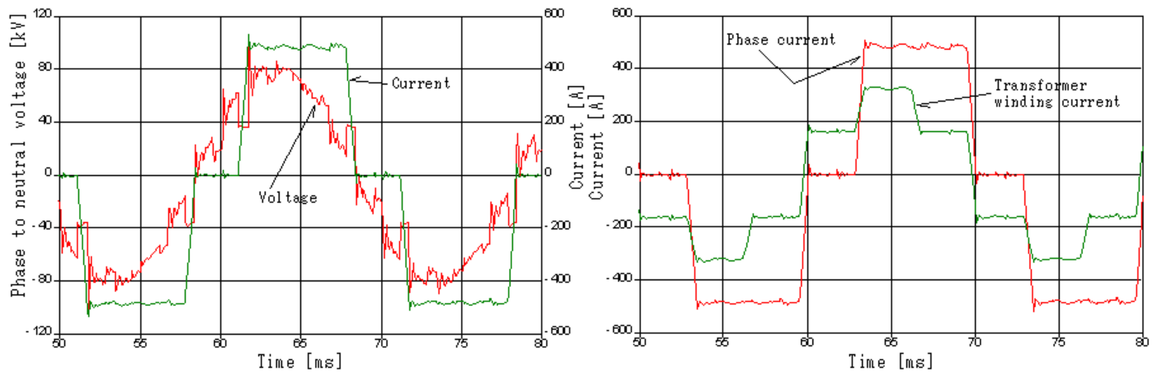
Fig. 9.1 a) and b) show basic HVDC converter and inverter respectively. In the figure only plus polarity units are shown. In actual cases, also minus polarity ones, which are the mirror image like, exist so the



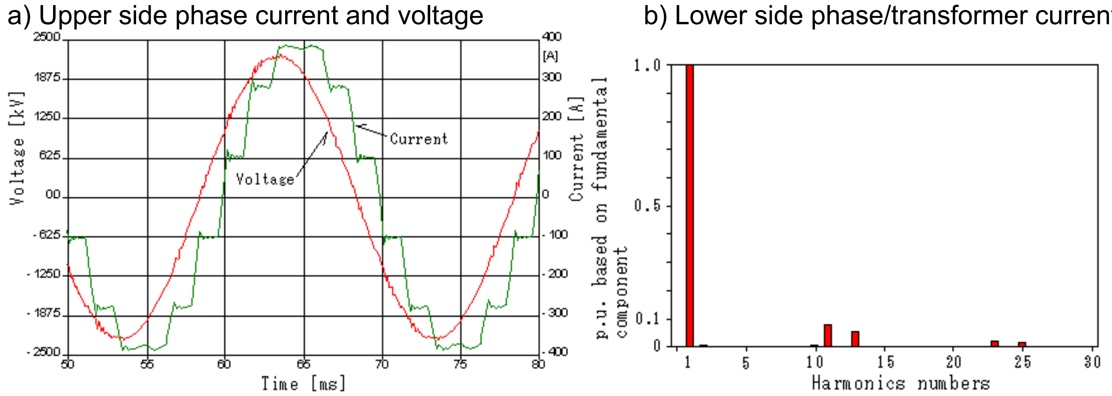
a) HVDC converter circuit b) HVDC inverter circuit

Fig. 9.1 HVDC converter/inverter circuit layout ---- Plus polarity only

ground (return) current is minimised.
In the figure, some supplemental elements, such as snubbers, capacitances around transformers, etc. are not shown. For details, see the attached data file.
Firstly the performance of the converter is surveyed. Connecting 50Hz source together with the source impedance to the left side, and load resistor to the right side, calculation is made. The key point is the timing of the gate signals. In the data file, TACS is applied for the purpose. Typical results are shown in

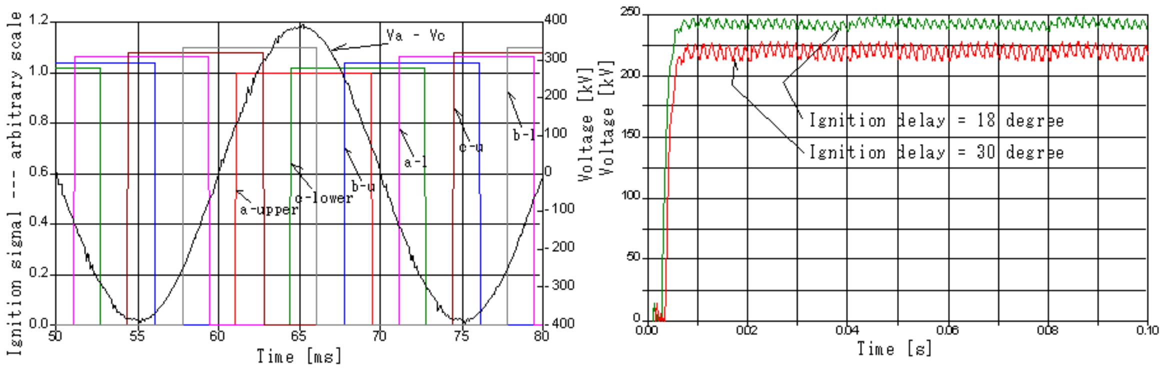


a) Upper side phase current and voltage b) Lower side phase/transformer currents



c) 50Hz system side phase current and voltage c) 50Hz current Fourier spectrum

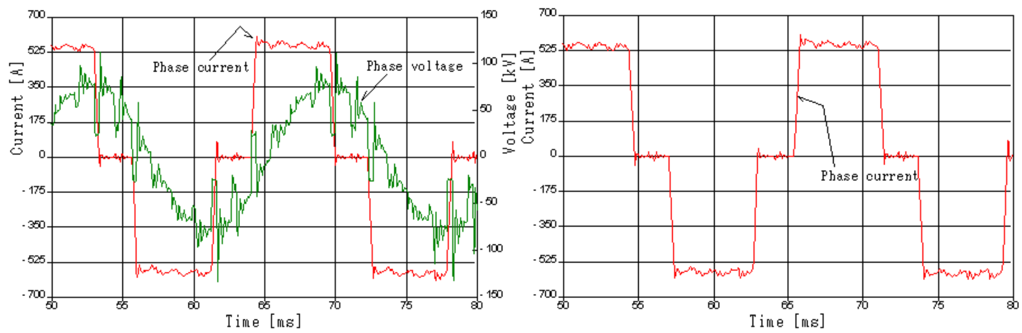
(Fig. 9.2 Converter circuit variables ------ continuing to the next page.)



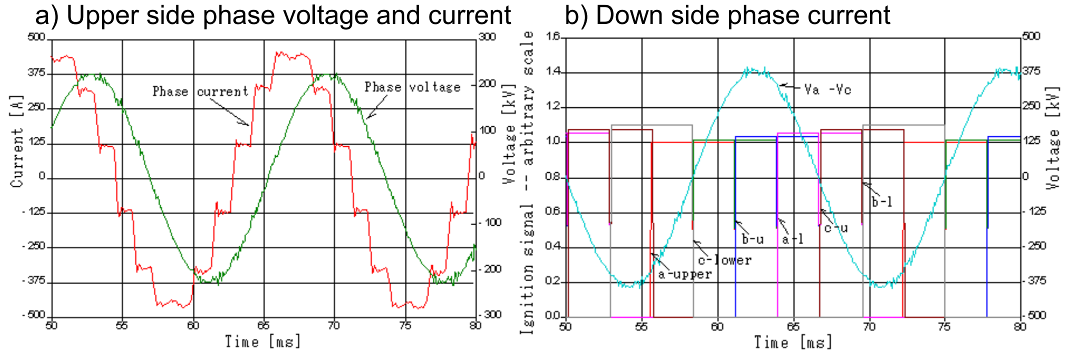
e) Upper side valve gate signals vs. voltage f) DC output voltage

Fig. 9.2 Converter circuit variables ----- continued from the previous page

Fig. 9.2.
As shown in the circuit diagram, valve switching side is constructed by two groups, the phase voltage angle difference between two groups is 30 degree by means of Delta/Star transformer winding connections. By such arrangement, higher DC voltage is easily obtained, and at the same time, harmonics in the AC side current is diminished. Fig. 9.2 a) --- d) show such effect. Each top or bottom side bridge phase current is square formed one. But, combining both side currents, AC side current is well formed. The effect is clearly shown in the Fourier spectrum (d), where low value of (12n $\pm$ 1)' order harmonics exist. Filter's capacity for eliminating such high frequency of harmonics can be rather low compared to lower frequency of harmonics.
Valve gate signals are to be based on the phase-to-phase voltage's phase angle, which is shown in Fig. 9.2 e). In the case, so called ignition delay angle (Alpha) is 18 degree. In f) output DC voltage is shown, together with the case of ignition delay (Alpha) equal to 30 degree. Theoretically, by primitive estimation, the output voltage is proportional to cosine of the delay angle (cosα). For further eliminating the ripple in DC, higher value of DC reactor can be applied.
Next, let's study externally communicated inverter circuit simulation. For higher capacity of systems such as power utility ones, due to economical and efficiency point of view, externally communicated systems are exclusively applied, where relatively cheep and high capacity of thyristers can be applied.
Connecting DC source to the right side of Fig. 9.2 b), where for easier understanding the directions of the



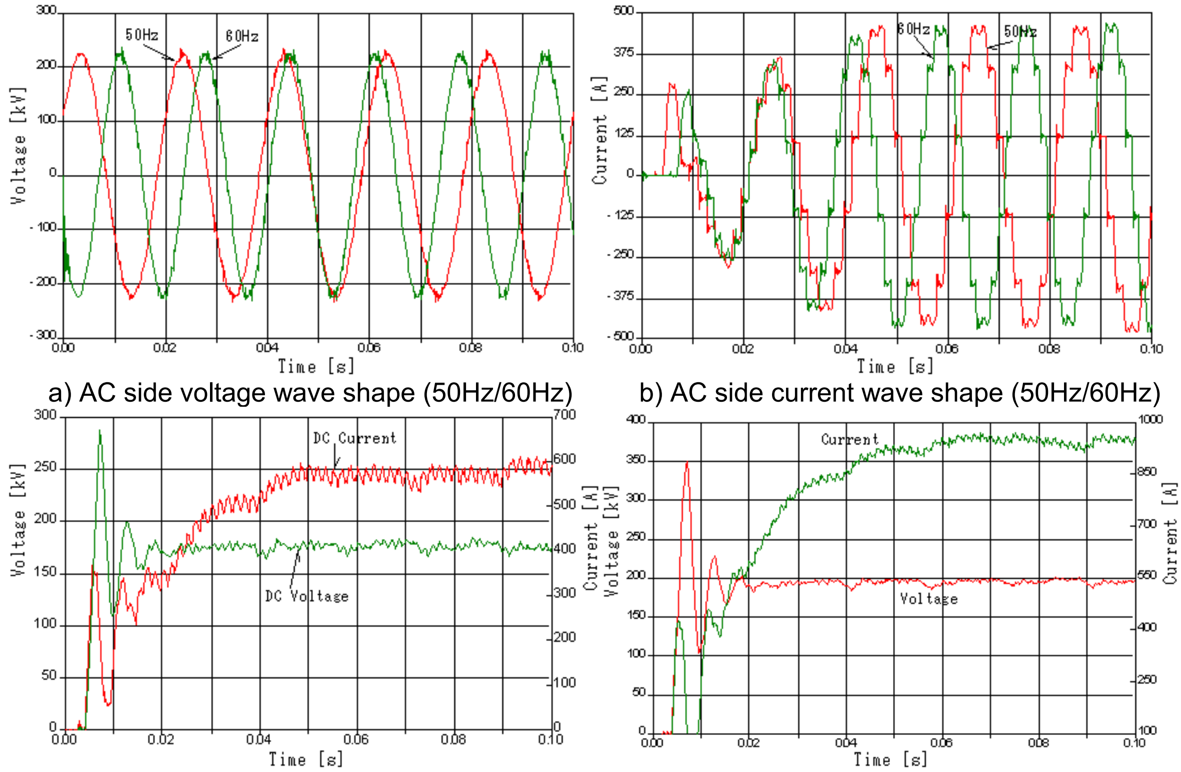
a) Upper side phase voltage and current b) Down side phase current



c) 60Hz AC side voltage and current d) Upper side valve gate signals vs. voltage

Fig. 9.3 Inverter variables ----- DC --- 60Hz AC

thyristers are reversed, and 60Hz of AC source to the left side, the performance is analysed. Some results are shown in Fig. 9.3.
It should be noted that the gate signal timing (for phase "a") is advanced from the zero point of the applied voltage (Va – Vc) as shown in d), resulting in normal externally communicating inverter performance. This is called advancing angle (Beta or β). Phase currents for both upper and down sides are square wave formed ones like in converter, and combining these in AC side via the Delta – Wye connected transformer, well formed AC current (60Hz) is produced. The current value is controlled by both DC voltage and advancing angle.
Finally, connecting the right side of the converter to the right side of the inverter, excluding DC source



a) AC side voltage wave shape (50Hz/60Hz) b) AC side current wave shape (50Hz/60Hz)

c) DC voltage and current, (α = 45 deg.) d) DC voltage and current, (α = 35 deg.)

Fig. 9.4 HVDC 50Hz – DC – 60Hz transmission system variables

and DC load resistor, single pole HVDC transmission system, transmitting power from 50Hz AC to 60Hz AC via DC transmission, is set up. The calculation results as for starting up of the system are shown in Fig. 9.4 Lower alpha corresponds to higher DC voltage and transmission power as shown in c) and d). In actual systems, high accuracy of gate ignition control seems to be most important.

9.2 SVC (Static Var Compensator/ Thyrister Controlled Inductor)

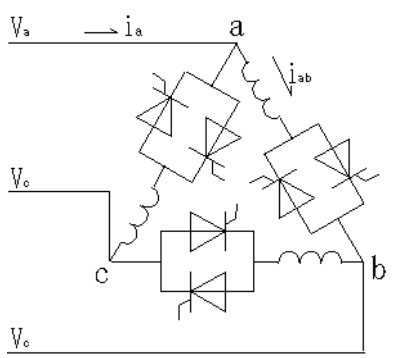
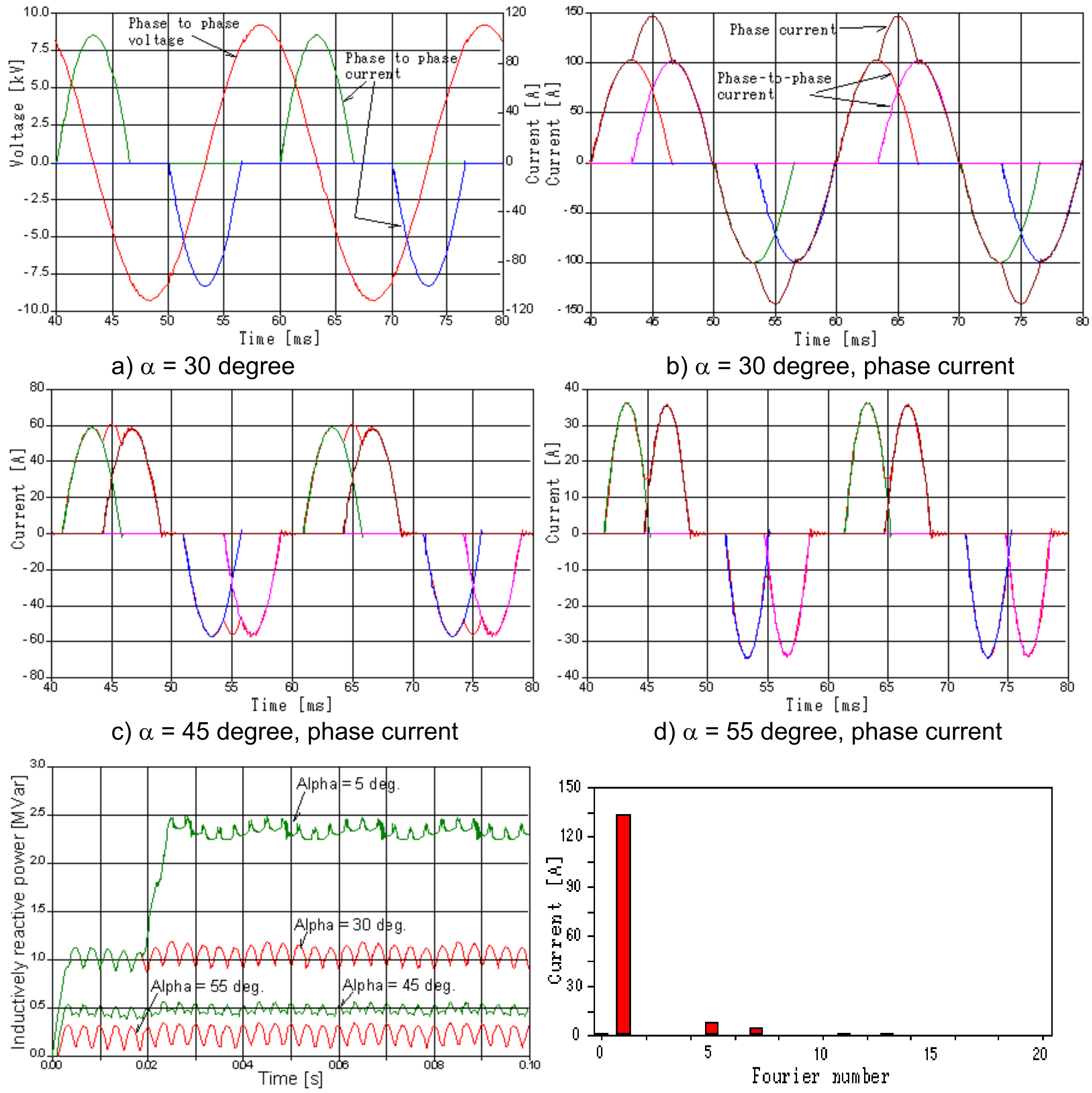


Fig. 9.5 Three-phase SVC circuit

As most-generally applied SVC, controlled inductor type is taken up. The system itself controls only inductively reactive power. For controlling also capacitively reactive power, capacitor bank is to be connected in parallel.
Fig. 9.5 shows basic three-phase SVC circuit, where some additional elements, such as snubbers, stray capacitances, etc. are not shown. For the continuity of the circuit, as the reactor current is not continuous, thyrister controlled inductors are installed between phases (Delta connection).
Detailed circuit constants are shown in the attached data files. By controlling the current flowing time-interval by thyrister in each cycle, the equivalent inductively reactive power is controlled. Narrow current window corresponds to lower reactive power. The current is no more sinusoidal.
Here, 6.6kV, 3000kVar (at maximum) three-phase SVC is analysed.



a) α = 30 degree
b) α = 30 degree, phase current
c) α = 45 degree, phase current
d) α = 55 degree, phase current
e) Reactive power vs. Alpha
f) Fourier spectrum of current in b)

Fig. 9.6 Thyrister controlled inductor performance

Some calculated results are shown in Fig. 9.6. SVC controlling is based on α (Alpha)---- ignition delay angle, by which the current flowing window is controlled, together with the crest value.

a) Phase to phase voltage and inductor current connected in between by α = 30 degree. The current is no more sinusoidal.
b) Phase current and within delta current at the top of the delta. The phase current wave shape is well formed. Fourier spectrum is shown in f).
c) Ditto but α = 45 degree.
d) Ditto but α = 55 degree
e) Reactive power calculated for α = 5, 30, 45, 55 degree. The calculation basis is 3-phase balanced sinusoidal wave shape, so the absolute values may be questionable. For the correct values, calculations based on the fundamental component of the Fourier spectrum are to be performed.
f) Fourier spectrum of the phase current in a)

9.3 PWM inverter, 3-phase, triangular carrier wave principle

The basic principle of PWM inverter is similar to DC step-down chopper, where constant frequency of pulses with constant crest value and width proportional to the target voltage (duty ratio) produces current approximately equal to one by the target value of DC voltage. By relatively slower change of pulse width, current change is similar to one by the corresponding voltage change. As the most primitive method to obtain appropriate pulse width, principle by triangular carrier wave shape compared to the target (reference) AC wave shape is often applied.

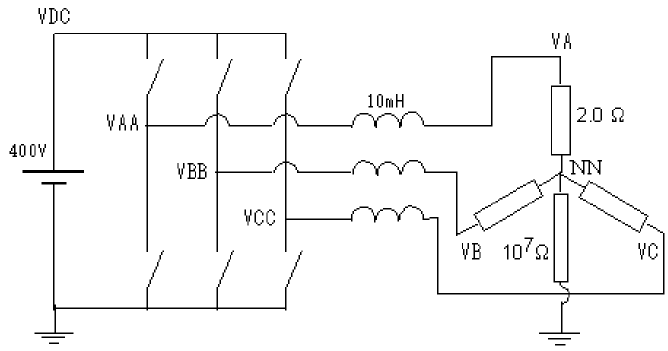


Fig. 9.7 3-phase PWM inverter circuit

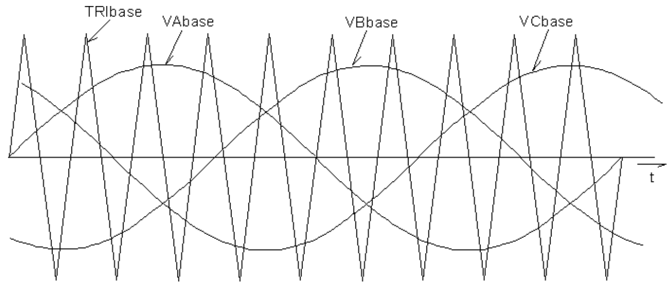
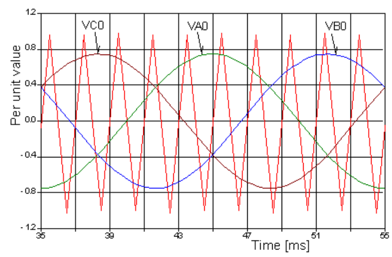


Fig. 9.8 Tri-angular & reference waves

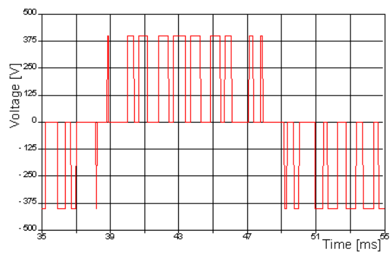
The principle circuit diagram is shown in Fig. 9.7. Some additional elements such as snubbers, stray capacitances, etc. are not shown in the figure. For details, refer the attached data files. When bi-polar switching elements are applied, the switching elements can be as shown in the figure. In case mono-polar switching elements such as GTOs, diodes are connected in parallel to the switching elements. Please refer some power electronics text books for details. In EMTP, No. 13 switching element is an ideal bi-polar switch, so circuit diagram as shown in the figure is applicable.

The control principle in Fig. 9.8, where tri-angular wave shape is compared to the reference voltage wave shape, can produce appropriate pulse width (duty ratio) corresponding to the phase-to-phase voltage.

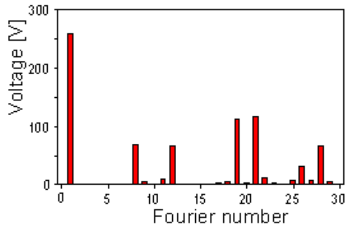
Care should be taken that, in Fig. 9.7, appropriate phase-to-phase voltage to the load circuit is produced, but the voltage at the neutral point (at NN) fluctuates. Therefore, the neutral can never be solidly earthed. For solidly earthed neutral load circuit, another circuit diagram is to be applied.



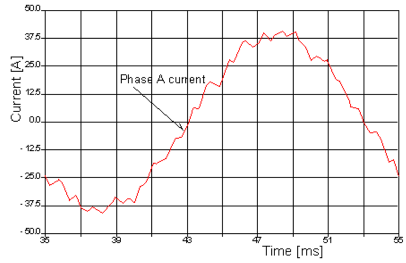
a) Control signals in TACS



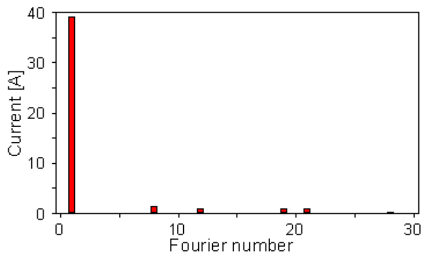
b) Phase A to phase B voltage



c) Fourier spectrum of b)



d) Current in phase A branch



e) Fourier spectrum of d)

Fig. 9.9 Some calculated results of PWM inverter in Fig. 9.7

Some calculated results are shown in Fig. 9.9. a) shows control signals in TACS by which gate signals to switch elements in the inverter are created. b) shows actual applied voltage wave shape to phase A to B. At approx. 40ms, the control signal VA0 – VB0 in a) is maximum. At that timing in b), pulse width is maximum, i.e. the pulse width is well controlled, proportional to the crest value of the voltage. c) shows Fourier spectrum of the voltage in b), where harmonics of the carrier wave frequency and its integral numbers are significant. As inductively reactive components are involved in the load circuit, harmonics in the load current is not significant as shown in d) and e).

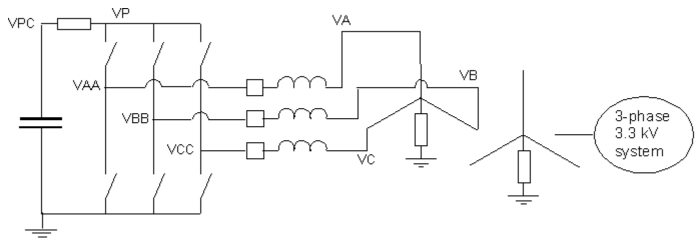
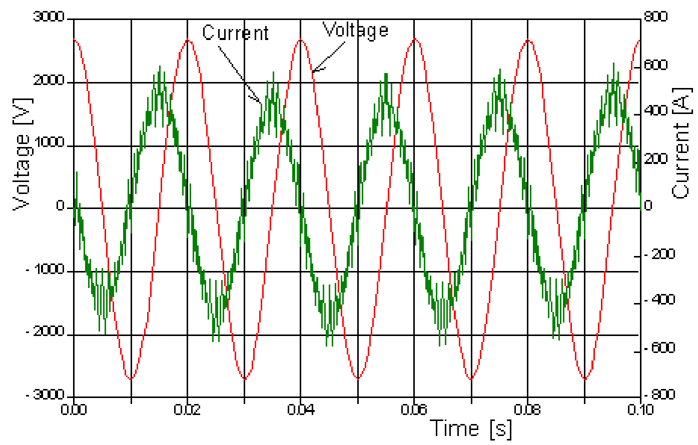
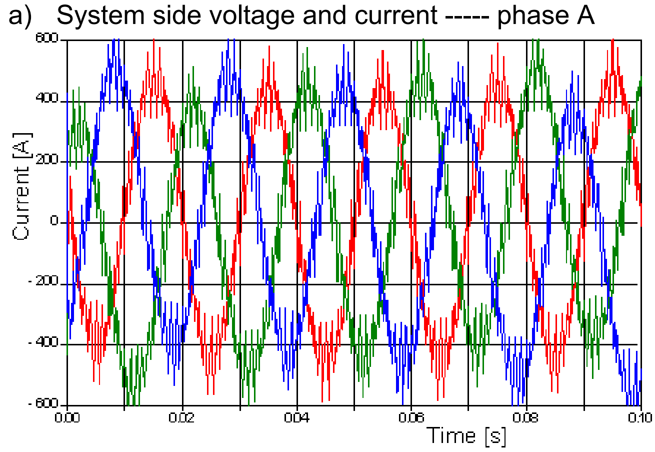


Fig. 9.10 Self-communicating static var compensator



a) System side voltage and current ----- phase A



b) System side 3 phase currents

Fig. 9.11 System side voltage and current under capacitively reactive power operation

As an application of PWM inverter, a self-communicated type static var compensator is shown in Fig. 9.10 which is the most simplified circuit diagram. A three-phase PWM inverter is connected to a power system via inductors. DC source can be a capacitor instead of voltage source. Any side of inverter or system is to be floating by this inverter circuit as shown before. So, in the case, the system side is high-ohmic resistor earthed transformer as shown in Fig. 9.10. Therefore, the transformer neutral voltage is much fluctuates.

Some calculated results are shown in Fig. 9.11. Depending charged voltage in the capacitor or target control voltage in the controller (i.e. TACS in the case), any of capacitively or inductively reactive power mode is applicable. For higher inverter side voltage than the system side, capacitively reactive mode is represented as shown in Fig. 9.11. In a), the leading current value is approx. 500A (crest), i.e. approx. 2MVA of capacitor mode operation.

As for details of the circuit parameters, see the attached data file.

Note:

- Miscellaneous elements such as stray capacitances, snubbers, etc. are excluded in the case. For detailed practical cases, such are to be introduced.
- In actual cases, especially for higher capacitance to earth involved cases, neutral floating system may not be appropriate.
- The initialisation in the calculation is complicated. In the calculation, the initialisation is not optimised.
- Relatively high capacitance value is necessary for the DC source capacitor. Also, relatively high carrier wave frequency is necessary. Try and error method seems to be suitable for survey the matter.
- The trapped voltage in the capacitor is controlled by phase angles between V_{cont} (inside reference voltage) and the system voltage, similarly to active power transmission control via an inductor.

9.4 Cycloconverter

For relatively low frequency of power source such as 10 --- 20 Hz, cycloconverters have been widely applied, the special feature of which is that high power and relatively low price thyrister is applicable as the switching valve element, and the efficiency is high due to direct frequency converting.

In Fig. 9.12 one-phase of cycloconverter circuit is shown, three sets of which compose a three-phase cycloconverter. In a three-phase cycloconverter, minimum 36 arms of switching elements are involved

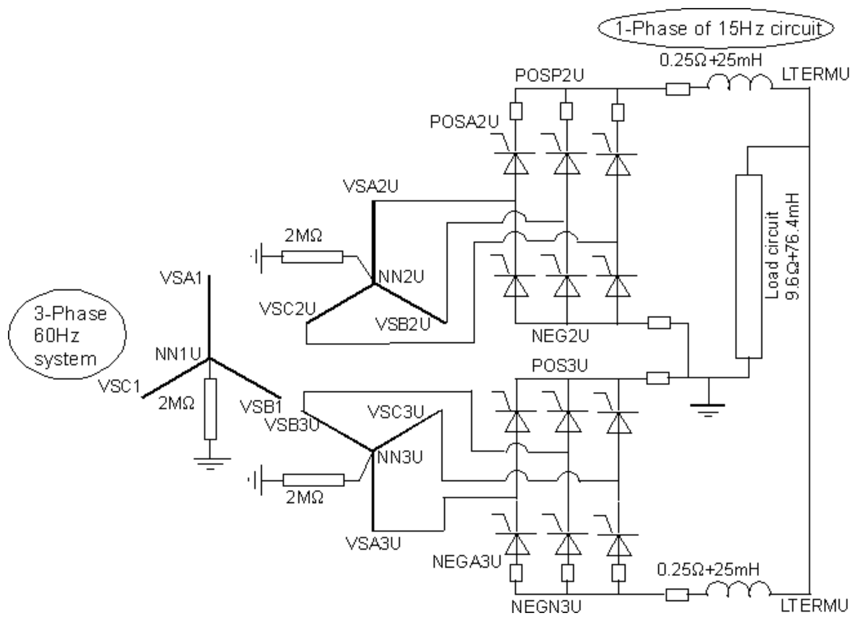
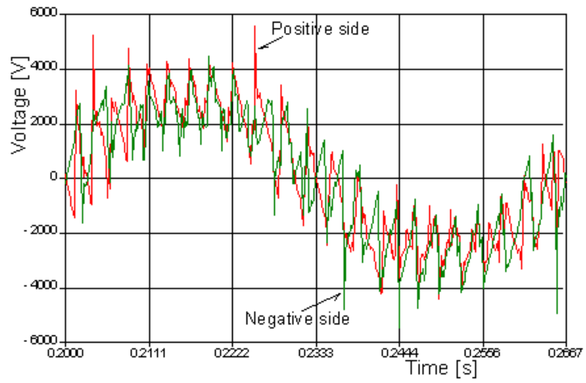
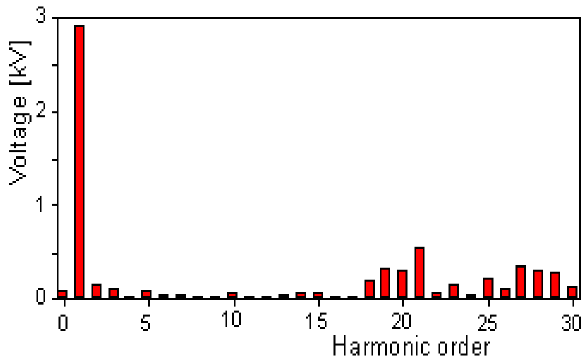


Fig. 9.12 One-phase of cycloconverter circuit

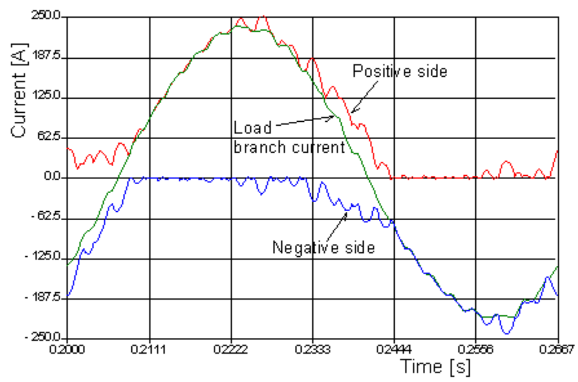
such as in the attached data file.
Each phase consists of plus and minus side blocks and one block is a three-phase thyrister rectifier bridge such as in Fig. 9.1 (converter). In thyrister converter circuit, as shown before, the out-put DC voltage is proportional to cosine α, where α is ignition delay angle, therefore by slow changing of α produces slow changing DC voltage. Therefore, in the upper side of the converter bridge in Fig. 9.12 can produce positive polarity of half wave, and lower side, negative polarity of one. Thus the circuit can produce relatively low frequency of alternating current. Turning over from one polarity to the other is to be smooth. In the case, fortunately automatic smooth turning over is obtained without any special means as shown later (Fig. 9.13c).
Some calculated results are shown as follows. :



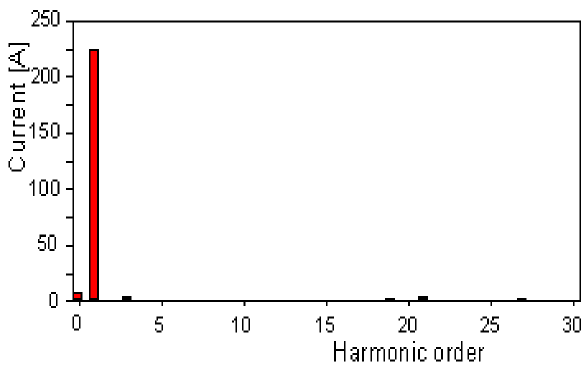
a) Across bridge voltages



b) Fourier spectrum of the voltage

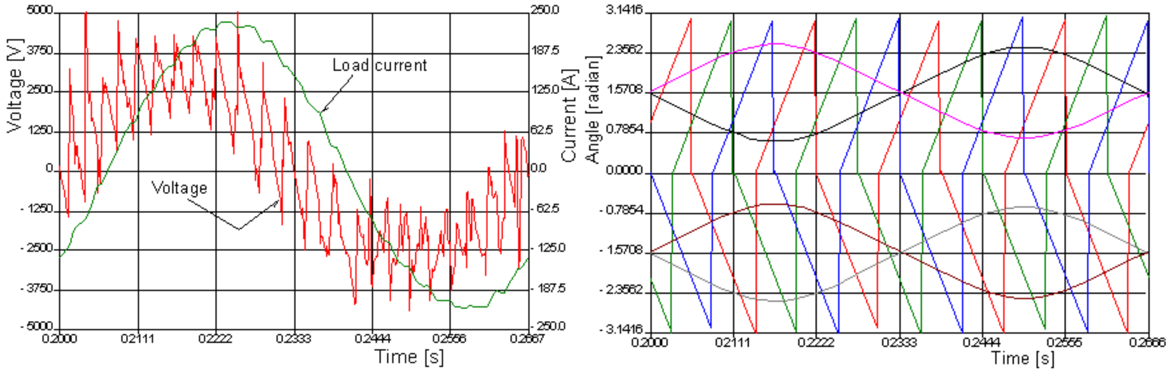


c) Through bridge & load currents



d) Fourier spectrum of the load current

Fig. 9.13 Cycloconverter variables (continuing)



e) Voltage and current of load

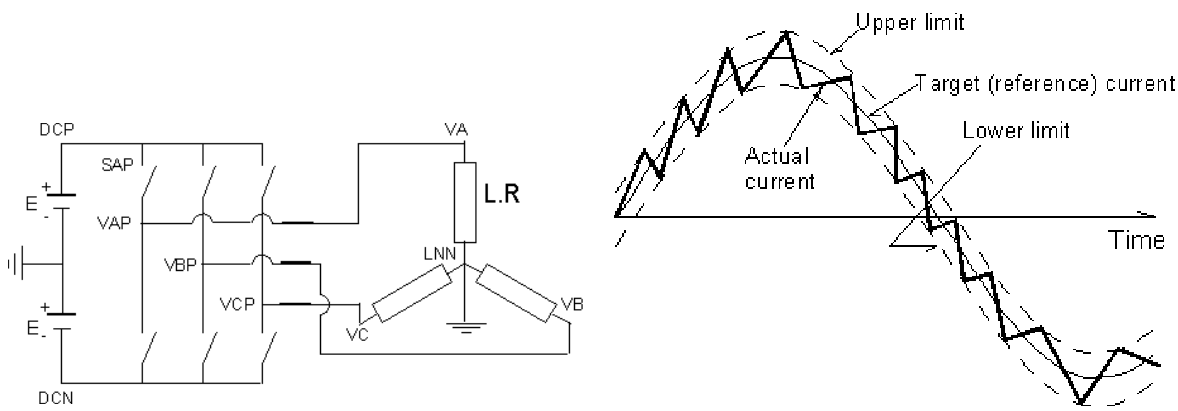
f) Ignition delay angle calculation basis

Fig. 9.13 Cycloconverter variables (continued)

f) shows the system (60 Hz) phase to phase voltage based saw teeth waves (three phase) and cosine of the target voltage basis (15 Hz), by which the ignition delay angles (alpha's) are calculated in TACS.
a) shows across-bridge voltages of both polarity converter bridges. Each bridge produces one polarity of voltage but due to the connection each other, both polarity of voltages are induced on the terminals.
b) shows the Fourier spectrum of the voltage, where relatively high order of harmonics are involved. Six times of switching per cycle are performed in the converter bridge and the out-put frequency is one forth of the system frequency. Therefore the number of harmonic orders are around 6 X 4 = 24.
c) shows both bridges' currents and the load circuit one. Around the load current zero time interval, circulating current through both bridges are observed, producing continuity of the load current at the zero.
d) shows the Fourier spectrum of the load current, which involves less harmonics, i.e. little distortion of the wave shape.
e) shows the load voltage and the current wave shapes. The instantaneous voltage in the power system including, especially, around the current zero time interval, are high. This corresponds to very low power factor of load current in the power system. This is typical demerit in cyclocoverter. Details will be shown in the next chapter regarding rotating machine driving application.

9.5 Current-regulated inverter ------ Hysteresis comparator

Similar inverter to one in Fig. 9.7 is applicable to current-regulated electric source, which will be applied in the next chapter as a current source for a doubly fed machine. As shown in the previous chapter, doubly fed machine requires quasi-current source for quick and stable controlling.



a) Current regulated inverter circuit

b) Current regulating principle

Fig. 9.14 Current-regulated inverter ------ Hysteresis comparator

The basic and most primitive circuit is shown in Fig. 9.14 a), where, for general applications, the neutral of both source and load are solidly earthed. Therefore, three independent phase controlling is possible. If source impedances, stray capacitances, etc. are introduced, for eliminating switching over-voltages, suitable snubber is to be attached. For non-bipolar switching elements, diodes are to be connected in

parallel to the switching elements. Current regulating principle is shown in Fig. 9.14 b). The actual current shows zigzag wave shape within the upper and lower limit band, the centre of which is the target reference current wave shape. Care should be taken that the switching frequency of the switching element is higher by narrower limit band and higher DC voltage. The minimum DC source voltage in Fig. 9.14 a) depends on the load impedance, the highest output current, internally induced voltage if any and the frequency. The gate signals for the switching elements can be composed in TACS as shown in the data file. See the attached data file. Dr./Prof. Ned Mohan (University of Minnesota), in the text book for ATP-Exercise, introduced an excellent algorism for the purpose, the principle of which is introduced also in the data file.
Some calculation results are shown below, where minimum possible DC voltage is applied. :

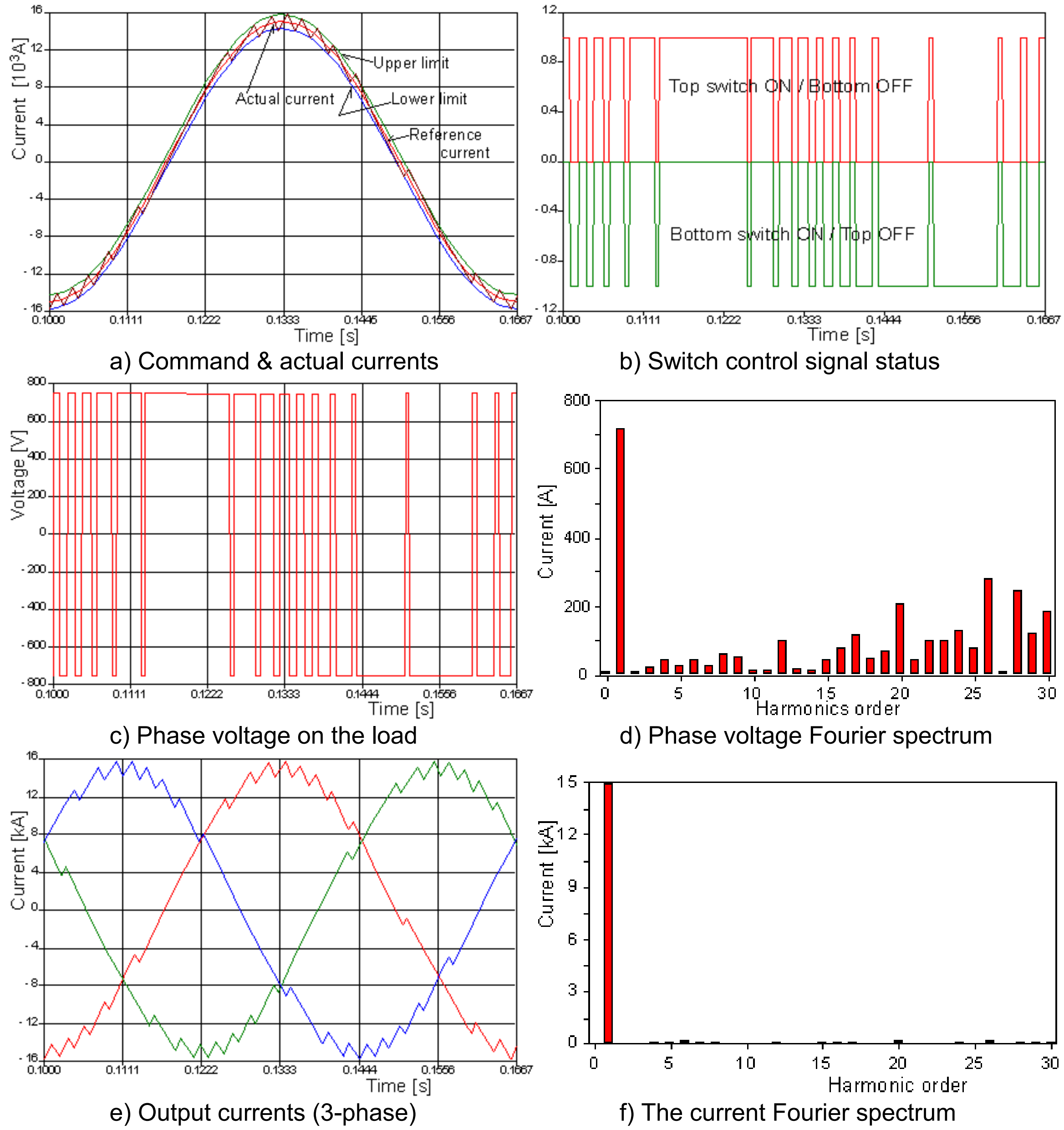


Fig. 9.15 3-phase hysteresis comparator output variables

As shown in a) and b), the current is well regulated within the tolerance band according to the hysteresis comparator principle. The voltage wave shape on the load circuit involves a lot of harmonics as shown in c) and d). But the current wave shape involves quite less harmonics, i.e. well regulated beautiful wave shape. There are fairly long time intervals with non-switching, i.e. constant DC voltage application. That shows the DC voltage value is critical (minimum possible) for the circuit condition.

Attached data files for this chapter

- Data9-01.dat : HVDC transmission converter circuit, 50Hz, 275kV – DC, 250kV, Alpha = 18 degree
- Data9-02.dat : HVDC transmission inverter circuit, DC, 250kV – 60Hz, 275kV, Beta = 120 degree
- Data9-03.dat : HVDC transmission circuit, 50Hz, 275kV – DC +250/-0 kV – 60Hz, 275kV, Alpha = 45 degree, Beta = 120 degree, approx. 100MVA transmission
- Data9-04.dat : Ditto, Alpha = 35 degree, Beta = 120 degree, approx. 150MVA transmission
- Data9-11.dat : 3-phase thyrister controlled reactor (SVC), 6.6kV, 1000kVA, Alpha = 30 degree
- Data9-12.dat : Ditto, but 500kVA, Alpha = 45 degree
- Data9-13.dat : Ditto, but 200kVA, Alpha = 55 degree
- Data9-14.dat : Ditto, but 3000kVA (Rated), Alpha = 5 dgree
- Data9-21.dat : 3-phase PWM inverter, basic/most simplified circuit
- Data9-22.dat : Ditto, but with DC source impedance elements involved
- Data9-23.dat : Ditto, but snubbers are connected
- Data9-24.dat : Ditto, but VVVF starting wave creating
- Data9-25.dat : 3-phase PWM inverter applied on SVG
- Data9-31.dat : 3-phase cyclo-converter circuit, creating 15 Hz of voltage from 60 Hz source
- Data9-41.dat : 3-phase current-regulated inverter circuit ---- hysteresis comparator