Matrix Converter : An Understanding
(A modular approach to design a converter suitable for variable frequency power supply applications)

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Abstract

The purpose of this study is to present the most wanted know-how about the concepts of single stage AC-AC conversion using Matrix Converter. It will illustrate the design of the system which can be used as power converter having applicability in variable frequency power supply applications like VFD's used in cement factories, ball mills, for maintenance of air-crafts when they are parked in their bays. The device is also likely to find the intensive application in Wind Power and Pico/Micro Hydro Generation so as to improve the efficiency of these power generation systems. This approach is through a modular design capable of providing variable speed constant frequency (VSCF) power generation. It is in this context that the basic aim of the present study revolves around the development of a converter useful for frequency changing power supply applications and later find the scope of its utilization for improvement of efficiency in areas like wind power generation and pico/micro hydro system, eliminating the mechanical interface in the forms of gear box and bearing mechanism, and thus minimizing the heavy losses taking place in the system responsible for reducing the overall system efficiency. The objective of the present study is limited only up to the development of matrix converter model by means of which input frequency can be converted to any desired frequency using 9 (nine) nos of simple bi-directional switches. In future course of time appropriate simulation through MATLAB will be done and required waveforms showing changed frequency will be generated. However, the instant presentation will deal only with presenting the knowledge based concept, illustrate about the functioning of the various features of the matrix converter and the comparison of existing AC-AC converters with that of proposed Matrix Converter. In future course of time the author of the present study withes to carry out extensive work on this issue including the proto development.

The scope of the present study is thus limited to propose the model and basic algorithm at this stage. In future course of time, simulate the design using MATLAB and generate the different waveforms for the required frequency output. Test the model for variability according to the nature of load i.e. resistive, resistive-inductive and purely motive and after simulation success suggest the integration of the model with DSP controller/filter so as to enable the model to be used for the purpose of variable speed constant frequency wind power and pico/micro hydro generation to enhance the efficiency of the overall system.

1. GENERAL INTRODUCTION

Having witnessed the severe oil crisis in the year 1973, the attention of the developed and developing economies of the world was focused on institutionalizing the measures related with that of finding the alternate and renewable resources of energy and optimally putting these resources to use for sustaining the technological development of the world. But, as the initial cost for tapping these resources was very high the immediate focus was shifted upon conservation of energy and thus controlling energy losses by energy efficient equipments and minimizing the losses related with the systems and the processes so that the widening gap between demand and supply can be apprehended. Conversion topologies provide avenues for reduction of losses involved in conversion process. Matrix Converter forms one of such areas that has specific importance not only from the view point of the technology but also focal point of effective means for reduction of losses in conversion process. Hence the present know-how is worth presentation so as to boost up and pave in the way for the design and development of such an energy efficient device.

2. REVIEW OF EARLIER STUDIES

After the development of controlled rectifiers in the year 1930, the first serious attempt in this direction was laid in 1964 by Schonung and Stemmler [1] who proposed the triangular carried-based sinusoidal pulse width modulation (PWM) strategy for three-phase inverter modulation. The space vector modulation (SVM) strategy was proposed by Pfaff, Weschta and Wick in 1982 [2]. They based the proposed SVM method on the development of new technology microprocessors. The SVM algorithm was improved by van der Broeck, Skudelny and Stanke [3]. This method became a basic modulation technique for three-phase PWM inverters. Pulse width modulated three-phase inverters can operate under voltage (open loop) or current (closed loop) control. Current-controlled systems have better performance and faster response than the voltage controlled systems because the control of the current is done in the inner loop of the control system [4]. AC industrial drives normally employ cascade control structure. It consists of multiple loops: the inner most loop is the current loop (which is the fastest), followed by speed loop and position loop. Implementing cascade control structure requires the current to be controlled. Good current controlled schemes should produce low current ripple, good tracking capability with zero steady state error, and fast dynamic response. The faster the response of the loop, the faster the disturbance is taken into consideration. The inner current loop in a servo motor drive plays a more important role than just limiting the current incase of overload. This loop operates continuously to regulate the motor developed torque so as to meet the load demand, and for meeting the speed trajectory specified by the motion controller. Motor drives of high dynamic response currently employ PWM current source [5]. In principle, all modulation schemes aim to create trains of switched voltage or current pulses which have the same fundamental volt-second or amp-second average (i.e., the integral of the waveform over time) as a target reference waveform. The major difficulty with these trains of switched pulses is that they also contain unwanted harmonic components which should, ideally, be minimized since they are injected to the mains and degrade the quality of energy. This degradation of energy cause malfunctioning of other equipments. The conventional SVM algorithm [7][8] usually generates both even and odd order harmonic voltages.

In 1980's extensive research work was carried out in the field of design and development of conversion topologies using controlled power devices. In this chain of developments, "Matrix Converters" were first mentioned in the early 1980's by Alesina and Venturini [6]. They proposed a general model and a relative mathematical theory for high-frequency synthesis converters. The AC-AC Matrix Converter is optimal in terms of minimum switch number and minimum filtering requirements. A three-phase AC-AC conversion requirement can also be met through a back to back cycloconverter, but it uses 36 thyristers thus making the system quite bulky. Also, each component used in the system itself is a loss leader, thus more the number of components used more will be the losses and hence the less efficiency of the overall system apart from the space constraints. This newly invented power converter eliminated the two stage conversion as in case of inverters (AC-DC-AC) and for the first time introduced the single stage conversion and was given the name as Matrix Converter (Alberto Alesina and Marco G. B. Venturini, \Solid-state conversion: A Fourier analysis approach to generalized transformer synthesis," *IEEE Transactions on Circuits and Systems*, vol. CAS-28, No. 4, pp. 319 {330, April 1981)", having very simple structure and many attractive features.

3. INTRODUCTION TO MATRIX CONVERTER

What is Matrix Converter

A Matrix Converter is a device used for converting directly AC energy into AC energy; the main feature of this device is to convert the magnitude as well as the frequency of the input into a desired magnitude and frequency of the output with an "all-silicon" solution. Mainly, a Matrix Converter consists of nine bi-directional switches, which are required to be commutated in the right way and sequence in order to minimize losses and produce the desired output with a high quality input and output waveforms.

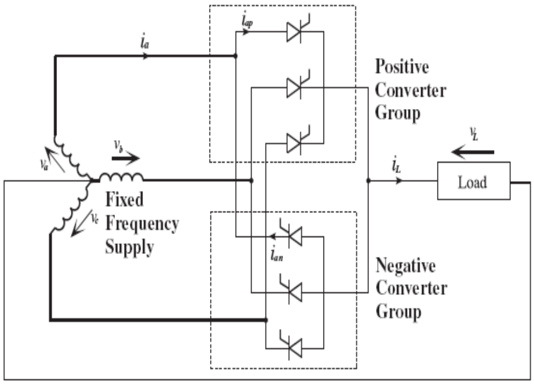
Matrix Converter and Cycloconverter :

After the controlled rectifiers were developed in the early 1930's, it was realized that this provided the possibility of generating alternating currents of variable frequency directly from a fixed frequency AC supply, the positive rectifier supplying the positive half cycles of current and the negative rectifier the negative half cycles. This system was called cycloconverter at its early stage and this proved to be so appropriate that nowadays it is still used in some high power applications because of high power requirements and the Matrix Converter technology is still not available widely. Moreover, most of the industrial applications require frequencies in the range of 50Hz-60Hz, which is easily obtained by the cycloconverter. For a three-phase to three-phase cycloconverter, 36 thyristor are required. This makes that cycloconverter systems are large and complicated and tend to be used in applications where high power is required (1MW and up).

Today, high power, multi-megawatts, thyristor based cycloconverter are very popular for driving induction and wound field synchronous motors. Some general applications of cycloconverter are:

1. Cement and ball mill drives.
2. Rolling mill drives.
3. Slip-power recovery Scherbius drives.
4. Variable-speed, constant-frequency (VSCF) power generation for air-craft 400Hz power supplies.

Frequency conversion or modulation techniques can be used to take a fixed frequency or DC source and provide any load with a different or variable frequency supply. Cycloconversion is mostly concerned with converting directly a low-frequency waveform into a desired different frequency waveform. A cycloconverter is an arrangement of two converter connected back to back as shown in Figure.



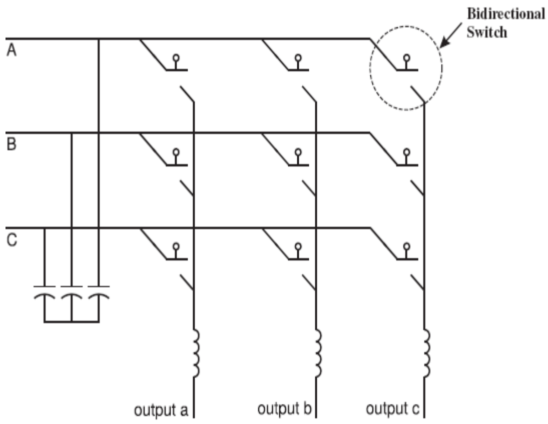


Figure 1.2: Structure of Matrix Converter.

Figure 3.1 Single-phase load fed from a three-pulse cycloconverter.

Matrix Converters were first mentioned in the early 1980's by Alesina and Venturini. They proposed a general model and a relative mathematical theory for high-frequency synthesis converters. They stated that the maximum input-output transformation ratio possible for the new AC-AC converter is $\sqrt{3}/2$ and also, they suggested a specific modulation and a feed-back-based control implementation of the proposed converter. The AC-AC Matrix Converter is optimal in terms of minimum switch numbers and minimum filtering requirements.

A three-phase AC-AC Matrix Converter consists basically of nine bidirectional voltage-blocking current-conducting switches. These switches are arranged in a matrix and by using this arrangement any input phase can be connected to any output phase at any time. Figure 1.2 shows such arrangement.

Statement of the problem

Eliminating the loss of energy involved in two stage conversion i.e. AC-DC-AC attracted the attention of many researchers. The quest got momentum with the model developed by Alesina and Venturini in 1980. But, unfortunately the concept could not be carried forward and hence could not gain the required popularity. Hence, it is desired through this incorporated small study to apprise about the envisaged Matrix Converter and propose the relative topology of AC-AC single stage conversion with the required frequency. The choice of frequency provided in this converter is capable of eliminating losses to tune of minimum 5-10% due to its single stage of conversion.

Formulation of the study

The Matrix Converters were basically designed for fulfilling the lighting and maintenance requirements of air-crafts when they are parked in their bays and also meant for VF drives in industrial setups. It also remains the fact that except the research at University of Nottingham, England, at no other place the advent of matrix converter took the momentum and almost left only for academic interest and practically unattended. In India too, no noteworthy extension is witnessed in this very important topology. However, the researcher of the present study finds that the latest area in which the possibility of its extensive use can be envisaged is “Wind Power Generation” and “pico/micro hydro generation”, provided a proper algorithm is built up and tested for converting the variable frequency input in to a fixed frequency output. Having recognized this area of use the researcher laid his hands on the fundamental work done by Alberto Alesina and Marco G. B. Venturini and the scalar model proposed by them.

Testing of the model may be done for variability according to the nature of load i.e. resistive, resistive-inductive and purely motive and after simulation success suggest the integration of the model with DSP controller/filter so as to enable the model to be used for the purpose of variable speed constant frequency systems to enhance the efficiency of the overall system.

Methodology

The envisaged model has been constructed on the basis of the fundamental work carried out by Alberto Alesina and Marco G. B. Venturini, way back in 1980. The proposed model has been constructed using the most widely used software in engineering applications i.e. MATLAB. The mathematical processing of the model is based upon the scalar model proposed by the same authors and the extensive work subsequently being carried out at the University of Nottingham.

The testing of the constructed model will be carried out by way of simulation and various waveforms will be generated for confirming the objectives set out in the study.

4. PRINCIPLE OF OPERATION

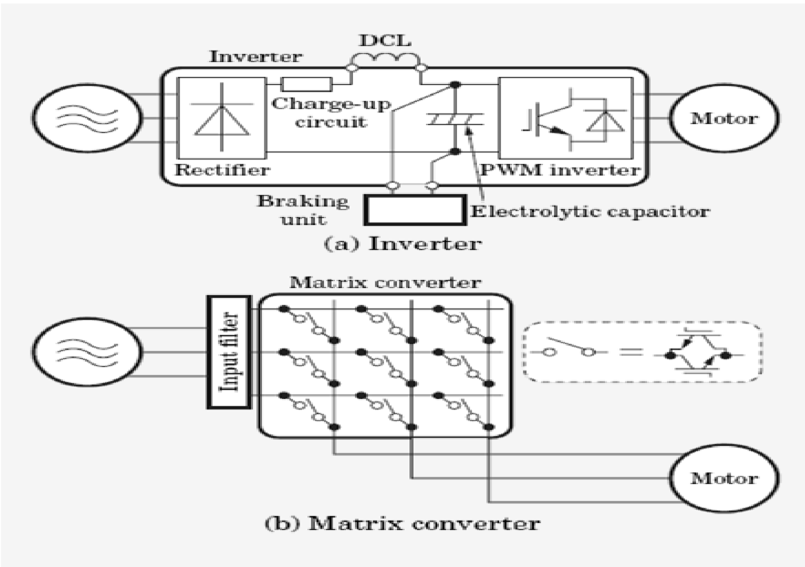
Principle of Inverter :

The inverter is well known devices that convert input AC voltage into DC voltage by a rectifier, and then control the semiconductor switch of a PWM inverter to convert to DC voltage into desired AC voltage. A voltage smoothing capacitor is required in DC link circuit, and an electrolyte capacitor is used for this purpose.

Principle of Matrix Converter :

On the other hand, the matrix converter arranges semiconductor switches into matrix configuration and them to convert input AC voltage directly into desired AC voltage. Since the input AC voltage is not converted to a DC voltage, there is no need of energy storage device such as electrolytic capacitor. Bi-directional switches are needed as the semiconductor switches, since an AC voltage is directly get output.

Figure 4.**1** Inverter and Matrix converter



As can be seen in Figure 4.1, the inverter required a charge up circuit to suppress the inrush that flow to electrolytic capacitor connected to DC link circuit. If a diode rectifier is used for converting AC voltage into DC voltage, a large amount of input current harmonics will be generated and therefore, a DC reactor (DCL) is inserted to reduce the harmonics in the input current.

Comparison of Matrix Converter with conventional system :

A PWM rectifier (inverter) was often used to reduce the input current harmonics and to realize motor regeneration. The matrix converter, on the other hand, is able realize motor regeneration with almost no input current harmonics. In other word, a single converter unit is able to provide performance equivalent to that of PWM rectifier and an inverter. Additionally, the charge up circuit is unnecessary since the large electrolyte capacitor is not needed for the matrix converter. As a result, smaller size longer lifespan can be achieved. In Figure 4.2, a matrix converter system is compared conventional system that uses of PWM rectifier and an inverter. The conventional system needs a filter reactor and boost-up reactor in additional to main unit. The matrix converter system, however, only need a main unit and filter reactor. Therefore the configuration becomes simple and panel size of the system can be reducing by ½ or more. In addition, **since the matrix converter uses one-stage AC-AC direct conversion, a low loss system can be realized, achieving at least 1/3 lower loss then in the conventional system.**

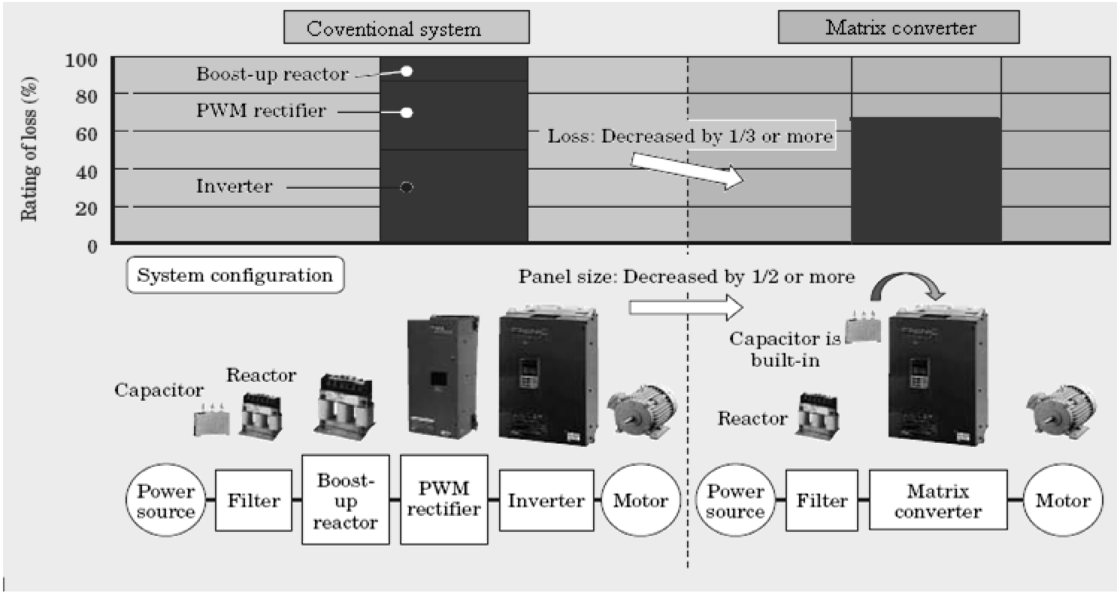


Figure 4.**2** Comparison of the matrix converter with the conventional system

5. CONTROL TECHNIQUE

AC to AC power conversion can be realized by using a rectifier stage and an inverter stage or by using a Direct or Matrix Converter (MC). A Matrix Converter uses only one conversion stage compared to two stages for the rectifier/inverter solution. Each converter topology has particular advantages and disadvantages, the choice, therefore, depends on the requirements of the application.

Matrix Converter Concept:

The power converter topologies used in industry can be grouped as follows:

- **Inverters:** used to change DC voltage or current to AC voltage or current. Inverters are widely used in variable-speed drives and AC power supplies.
- **Rectifiers:** used to change AC voltage or current (usually from a grid supply of 50 or 60Hz) to DC voltage or current.

Rectifiers and inverters are often combined to form indirect AC to AC Converters, as shown in Figure 5.1 drive system. As it can be seen in the figure, the Matrix Converter circuit consists of an array of nine bi-directional switches constructed from unidirectional power devices, arranged in such a way as to enable any input line to be connected to any output line at any time. The switch duty cycles are modulated to generate the desired output waveform on the basis of the input supply voltages and the demanded output voltages. The demanded voltages are generally the output of a cascaded speed and current control loop. A Matrix Converter can be viewed as an "all-silicon solution" to the general AC-AC power conversion problem. Compared to the conventional rectifier/inverter topology, Matrix Converters have many advantages. No DC-link energy storage is required for the Matrix Converter topology. This removes the necessity for bulky electrolytic capacitors, which are intolerant to high temperatures and have a relatively short life time. As a result of the elimination of the DC-link a potentially compact converter system can be designed.

To understand the modulation problem and its solution, consider the arrangement shown in Figure 5.2. The fundamental requirement can be stated as follow; a balanced set of three-phase input voltages is expressed as,

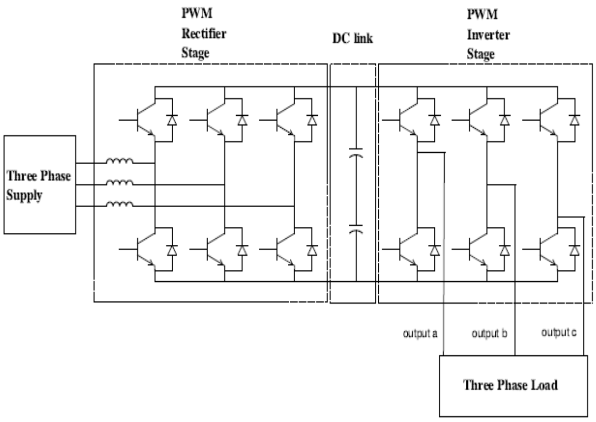


Fig. 5.1: Schematic of AC to AC converter.

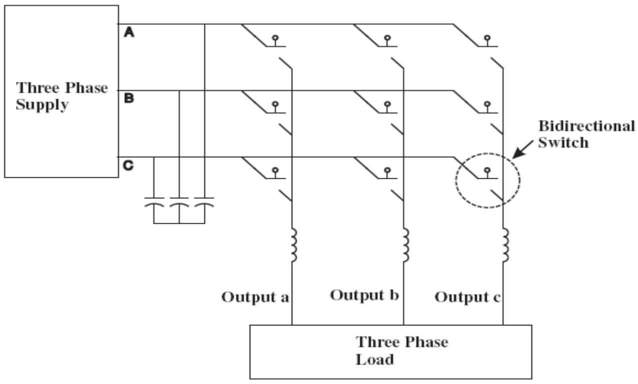


Fig. 5.2: Simplified representation of a Matrix Converter system.

$$[\mathbf{V_i(t)}] = \begin{pmatrix} V_{i1}(t) \\ V_{i2}(t) \\ V_{i3}(t) \end{pmatrix}$$ ----- (3.1)

Where,

$$[\mathbf{V_i(t)}] = \begin{pmatrix} V_i cos(\omega_i t) \\ V_i cos(\omega_i t - 2\pi/3) \\ V_i cos(\omega_i t + 2\pi/3) \end{pmatrix}$$ ----- (3.2)

With these input voltages the switching function *M*(*t*) that will produce a set of desired three-phase output voltages can be determined, Where,

$$[\mathbf{V_o(t)}] = \begin{pmatrix} V_{o1}(t) \\ V_{o2}(t) \\ V_{o3}(t) \end{pmatrix}$$ ----- (5.3)

$$[\mathbf{V_o(t)}] = [M(t)].\begin{pmatrix} V_{i1}(t) \\ V_{i2}(t) \\ V_{i3}(t) \end{pmatrix}$$ ----- (5.4)

$$[\mathbf{V_o(t)}] = \begin{pmatrix} V_o cos(\omega_o t + \theta_o) \\ V_o cos(\omega_o t + \theta_o - 2\pi/3) \\ V_o cos(\omega_o t + \theta_o + 2\pi/3) \end{pmatrix}$$ ----- (5.5)

Where, θ_o is an arbitrary output voltage phase angle. The switching function, *M*(*t*), must satisfy the previous stated conditions. Several modulation strategies have been proposed. These modulation strategies give different voltage conversion ratios and the number of commutations employed in each modulation strategies is different.

Modulation Techniques:

In principle, all modulation schemes aim to create trains of switched voltage or current pulses which have the same fundamental volt-second or amp-second average (i.e., the integral of the waveform over time) as a target reference waveform. The major difficulty with these trains of switched pulses is that they also contain unwanted harmonic components which should, ideally, be minimized since they are injected to the mains and degrade the quality of energy. This degradation of energy cause malfunctioning of other equipments.

The first modulator proposed for Matrix Converters, known as the Venturini modulation, employed a scalar model. This model gives a maximum voltage transfer ratio of 0.5. An injection of a third harmonic of the input and output voltage was proposed in order to fit the reference output voltage in the input system envelope. This technique is used to achieve a voltage transfer ratio with a maximum value of 0.866. In this analysis, a three-phase input, three-phase output converter is considered. Because the Matrix Converter is symmetrical, the designation of input and output ports is arbitrary. However, for any sensible mode of operation, one port should be considered to have a voltage stiff characteristic and the other port a current stiff characteristic. In this case stiff means that the voltage or current must be constant with no interruptions or sudden variations. For the following analysis it is assumed that the input port is voltage stiff and the output port is current stiff. In a practical Matrix Converter an input filter is included to circulate the high frequency switching harmonics and provide the voltage stiff characteristic. The output inductance is usually part of the load giving a current stiff characteristic. This study considers that upper case suffixes always denote the input phases and lower case suffixes denote the output phases as shown in Figure 5.2.

The concept of switching functions is used to derive a mathematical model of the Matrix Converter. Ideal switching is assumed in this analysis. The switching function, *SKj* , is defined as the representation of the switch connecting input line *K* to output line *j*. When the switch is ON, the switching function has a value of 1 and when the switch is OFF, the switching function has a value of 0. The instantaneous current and voltage relationships can then be written as given in Equations 5.6. One of the most important rules that Matrix Converters must obey is the one expressed by Equation 5.7. This equation states that at any instant one and only one switch on each output phase must be closed. Analyzing the arrangement shown in Figure 5.2, which shows that there are no freewheeling diodes, this restriction means that the short circuit in the capacitive input as well as the open circuit in the inductive output must be avoided. For the following analysis, it is assumed that Equation 5.7 is obeyed and, because ideal switches are used, the commutation between switches is instantaneous.

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \quad \text{---- (3.6)}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ab}(t) & S_{Ac}(t) \\ S_{Ba}(t) & S_{Ba}(t) & S_{Bc}(t) \\ S_{Ca}(t) & S_{Cb}(t) & S_{Cc}(t) \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}$$

$$\sum_{K=A,B,C} S_{Ka}(t) = \sum_{K=A,B,C} S_{Kb}(t) = \sum_{K=A,B,C} S_{Kc}(t) = 1 \quad \text{--- (3.7)}$$

A typical switching pattern for Matrix Converter is shown in Figure 3.3. If conventional PWM is employed the switching sequence *Tseq* has a fixed period.

$$m_{Aa}(t) = \frac{t_{Aa}}{T_{seq}} \quad \text{------ (5.8)}$$

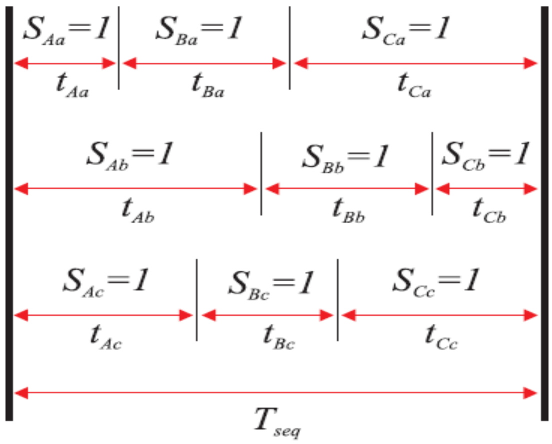


Figure 5.3: General form of switching pattern.

A modulation duty cycle should be defined for each switch in order to determine the average behavior of the Matrix Converter output voltage waveform. A modulation duty cycle should be defined for each switch in order to determine the average behavior of the Matrix Converter output voltage waveform. The modulation duty cycle is defined by equation 3.8., where t_{Aa} represents the time when switch S_{Aa} is ON and T_{seq} represents the time of the complete sequence in the PWM pattern. The modulation strategies are defined by using these continuous time functions. Equation 3.9 shows the use of these functions for the three-phase Matrix Converter.

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t) \\ m_{Ac}(t) & m_{Bc}(t) & m_{Cc}(t) \end{bmatrix} \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \text{ ----- (5.9)}$$

$$\begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} = \begin{bmatrix} m_{Aa}(t) & m_{Ab}(t) & m_{Ac}(t) \\ m_{Ba}(t) & m_{Ba}(t) & m_{Bc}(t) \\ m_{Ca}(t) & m_{Cb}(t) & m_{Cc}(t) \end{bmatrix} \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix}$$

$$[v_o(t)] = [M(t)][v_i(t)]$$
$$[i_i(t)] = [M(t)]^T[i_o(t)] \text{ ------ (5.10)}$$

Voltages *va*, *vb* & *vc* and currents *ia*, *ib* & *ic* in Equation 5.9 are now values averaged over the sequence time.

In Equation 5.10, which is a representation in a more compact notation of Equation 5.9, the matrix *M*(*t*) is known as the *modulation matrix*.

6. FINAL DESIGN OF THE PROPOSED MODEL

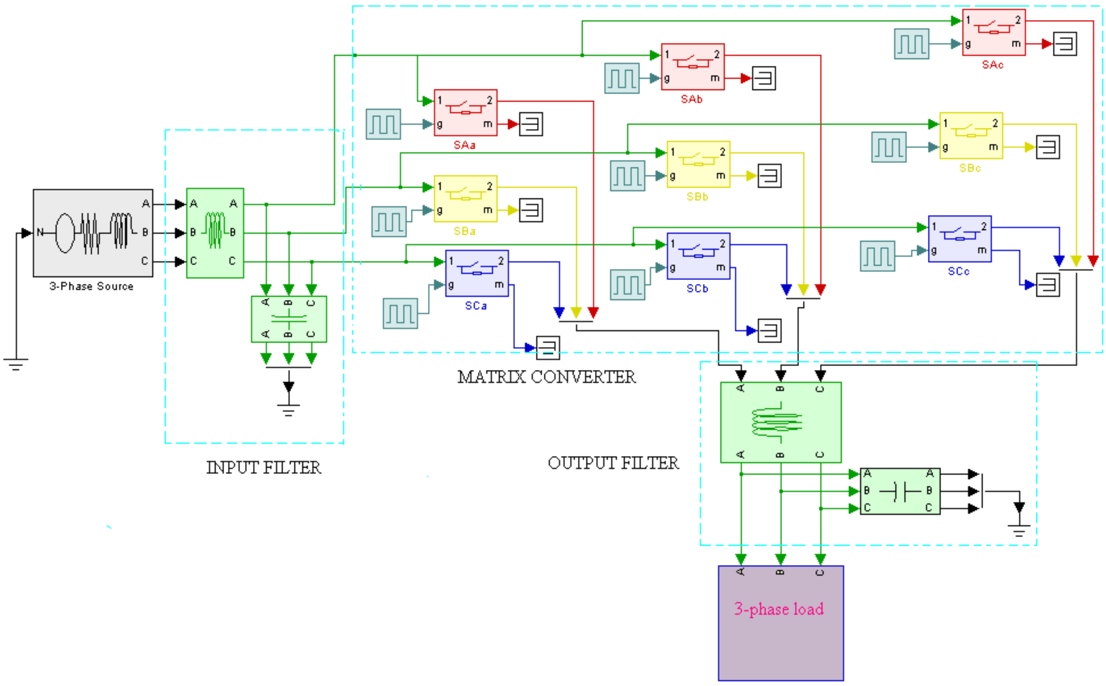


Figure 4.1: Schematic of Matrix Converter used in MATLAB simulation.

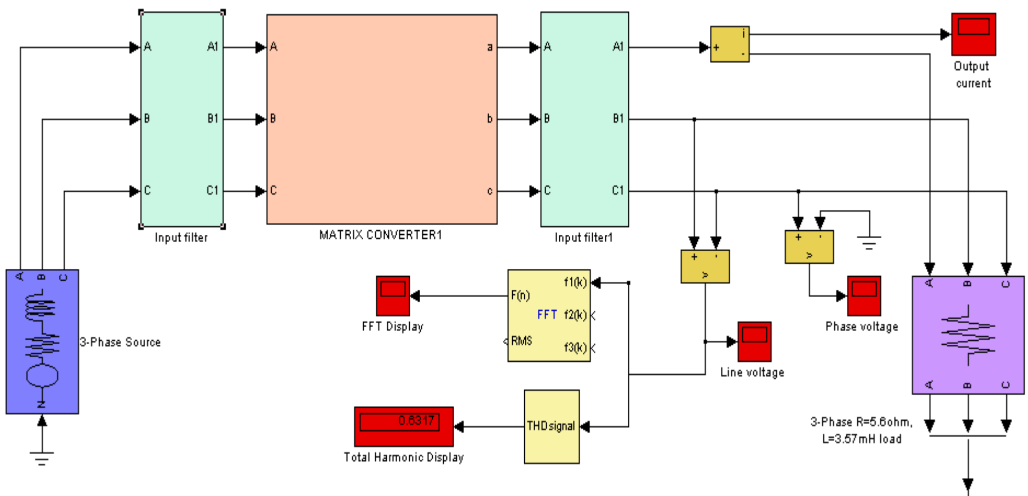


Figure 4.2: Schematic of Matrix Converter used in MATLAB simulation

7. CONCLUSIONS

The Matrix Converters were basically designed for fulfilling the lighting and maintenance requirements of air crafts when they are parked in their bays and also meant for VF drives in industrial setups. It also remains the fact that except the research at University of Nottingham, England, at no other place the advent of matrix converter took the momentum and almost left only for academic interest and practically unattended. In India too, no noteworthy extension is witnessed in this very important topology. However, it is envisaged that the latest area in which the possibility of its extensive use can be witnesses is, "Wind Power Generation" provided a proper algorithm is built up and tested for converting the variable frequency input in to a fixed frequency output.

The author proposes to carry on further study related to the working of matrix converter with different loads by means of simulating and testing the model. For simulation MATLAB software will be used. However, after achieving the success in generating the wave forms showing conversion of fixed frequency to variable frequency output, the reverse algorithm would be proposed to generate fixed frequency output from the variable frequency input which would be used in wind power generation which can be termed as variable speed constant frequency converter (VSFC). The use of a Matrix Converter so designed would definitely be great help in enhancing the wind power generation efficiency to a significant extent. However, the design also necessitates the application of DSP controller/filter which can suitably scan the input rotation/frequency and then send the signal to multistage Matrix Converter, each stage would mean a different input frequency and give a constant frequency output.

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