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Performance Analysis of Electric Locomotive using Matrix Converter

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Abstract

The conventional type electric locomotive consists of traction transformer, traction converter and three phase induction motor. The conventional type traction converter contains rectifier and inverter which makes it huge, less efficient and difficult to maintain. In this research, the conventional traction converter is replaced by a single matrix converter (AC to AC converter) with bidirectional switches. The proposed converter is analyzed using different Pulse Width Modulation techniques namely sinusoidal pulse width modulation, and space vector pulse width modulation, and the performance of proposed converter is observed by using MATLAB.

Keywords: Matrix Converter, PWM techniques, traction motor, Total Harmonic Distortion.

1. Introduction

A locomotive, also referred to as an engine, is a kind of rail transportation vehicle that provides the motive force to move a train. Locomotives with consists of fueled prime movers, such as diesel engines or gas turbines, are called as diesel-electric or gas turbine-electric rather than electric locomotives. A locomotive that runs only on electricity is called an electric locomotive.

The power supply for an electric locomotive can come from the grid, a third rail, or the locomotive's own batteries or supercapacitors. The electric generator/motor system basically functions as a power transmission system. A channel typical electric locomotive will have an

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efficiency of around 90% attributed to the electric motor (that is, excluding the inefficiency of electricity generation). Regenerative braking utilises the kinetic energy created by the brakes to power electrical systems during acceleration, hence boosting productivity. Modern electric locomotives can benefit from regenerative braking according to the Alternating Current (AC) motor with inverter included into their driving systems.

Electric trains never makes so much noise. The power for an electric locomotive comes from different sources such as, rechargeable energy storage devices that can be charged, such as batteries or ultracapacitors, constant power supply such as an overhead wire, etc. In general, electric locomotives can be identified by the following unique components: the type of electrical power supply used, Alternating Current (AC) or Direct Current (DC), Traction transformer, Traction converters, and Traction motor.

2. Matrix Converter

A. Definition

A matrix converter is a device that converts an alternating current input supply to a variable alternating current supply as an output without the need of any channel conversion processes. Matrix converter is a type of AC to AC converter and it has regenerative power flow capability. It can be achieved by bidirectional switches.

B. Single Phase Matrix Converter

Single-phase matrix converter converts fixed single phase AC to variable single phase AC. Topologies use a matrix of 4 bidirectional switches to connect the power source input to the load output at each intersection. Single-phase matrix converter works as the principle of various converter like rectifier, inverter, cycloconverter and more by just changing the switching sequence, and it has special characteristics like bidirectional power flow.

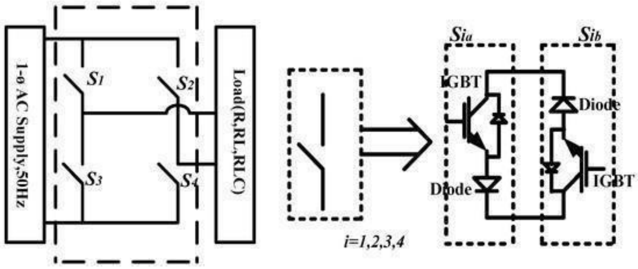

Figure 1. Circuit Diagram of Single Phase Direct Matrix Converter [7]

Single phase matrix converter working principle depends uponthe switching sequences of the four bidirectional switches, and it can be controlled by modulation techniques.

The above table shows the switching sequence of four bidirectional switches, and it can be controlled by the modulation techniques.

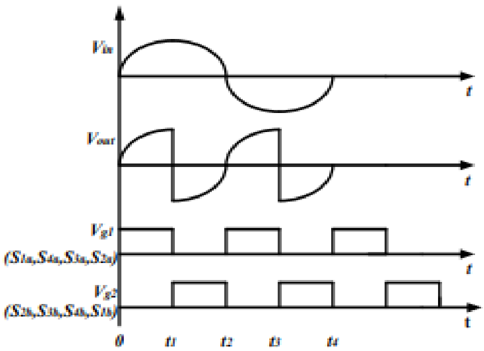

Figure 2. Output Voltage Waveform of Matrix Converter

The above figure represents the matrix converter’s output voltage waveform.

C. Three Phase Matrix Converter

Theoretically, the matrix converter's nine bidirectional switches allow for 512 (or 29) distinct switching states. However, only few of these have any practical use which to connect the power source input to the load output at each intersection. Three Phase Matrix Converter works as principle of various converters like rectifier, inverter, cycloconverter and more by just changing switching sequence and also have special characteristics like bidirectional power flow.

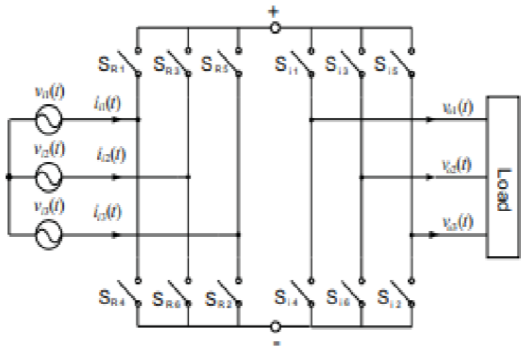

Figure 3. Circuit Diagram of Three Phase Direct Matrix Converter [14]

Three phase matrix converter working principle depends upon the switching sequences of the nine bidirectional switches, and it can be controlled by different modulation techniques with switching configuration.

Table 1. Switching Configuration of 3-phase matrix converter [15]

Rectifier Stage		Inverter Stage	
Active Vector	Switch turned on	Active Vector	Switch turned on
$\mathbf{I_1}$	S_{R1}, S_{R2}	$\mathbf{V_1}$	S_{I1}, S_{I6}, S_{I2}
$\mathbf{I_2}$	S_{R2}, S_{R3}	$\mathbf{V_2}$	S_{I1}, S_{I3}, S_{I2}
$\mathbf{I_3}$	S_{R3}, S_{R4}	$\mathbf{V_3}$	S_{I4}, S_{I3}, S_{I2}
$\mathbf{I_4}$	S_{R4}, S_{R5}	$\mathbf{V_4}$	S_{I4}, S_{I3}, S_{I5}
$\mathbf{I_5}$	S_{R5}, S_{R6}	$\mathbf{V_5}$	S_{I4}, S_{I6}, S_{I5}
$\mathbf{I_6}$	S_{R6}, S_{R1}	$\mathbf{V_6}$	S_{I1}, S_{I6}, S_{I5}
$\mathbf{I_7}$	S_{R1}, S_{R4}	$\mathbf{V_7}$	S_{I1}, S_{I3}, S_{I5}
$\mathbf{I_8}$	S_{R3}, S_{R6}	$\mathbf{V_8}$	S_{I4}, S_{I6}, S_{I2}
$\mathbf{I_9}$	S_{R5}, S_{R2}	-	-

The output voltage is controlled by the pulse width modulation techniques, and the output voltage waveform of three phase matrix converter is shown below.

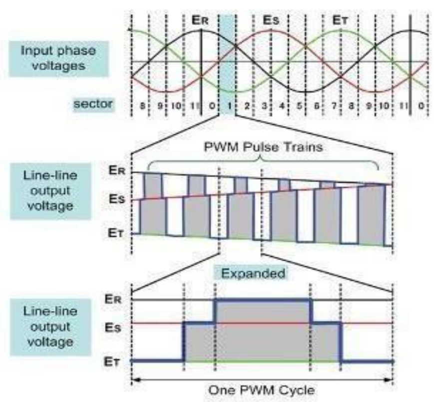

Figure 4. Output Voltage Waveform of Three Phase Matrix Converter [8]

D. Single Phase to Three Phase Matrix Converter

Implementing converter to operate three-phase loads from a single-phase supply is possible. This converter is ideal for single-phase applications including house, remote town, and mobile electricity. Higher load conditions are uneconomical for single phase induction motors beyond 0.5 kW. This is usually applied in rural areas, the conversion from single to three phase is depicted in fig.5 below.

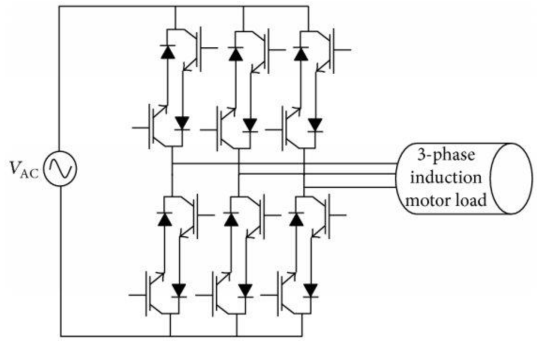

Figure 5. Circuit Diagram of SP2TP Matrix Converter [8]

E. Design and Working of SP2TP Matrix Converter

The term "space vector pulse width modulation technique" refers to a method of transforming three-phase voltages or currents into a single space vector component that is proportional to all three phases. The resulting vector component is called a space vector since it is a spatial equivalent. Space Vector Modulation (SVM) can be achieved ina variety of ways. The RMF theory is utilised in the space vector modulation method, in the prompt resultant flux of the three phase. The synchronous rotation of the field is produced by alternating fluxes that are 120 degrees apart.

The three-phase sinusoidal currents are shown below:

$$ia = Im \sin wt,$$
$$ib = Im \sin (wt - 120)$$
$$ic = Im \sin (wt - 240)$$

Three sinusoidal currents create three sinusoidal alternating fluxes that are equal in amplitude and 120° apart in a three- phase system. When the "a-phase" current "ia" reaches its maximum value and equals "Im," the currents in other phases "ib" and "ic" are negative with magnitudes of,

$$ib = Im \sin (-30)$$
$$ic = Im \sin (-150)$$

Thus, the fluctuating fluxes yield 1.5 times the maximal flux (ϕm). The maximum flux density provides sinusoidal flux distributions with maximum values that trace a circle for any three-phase sinusoidal excitations.

Two-phase systems with identical magnitude and 90° voltage differences can yield a comparable spinning resultant flux. These fluxes have α and β components. The α and β fluxes can be determined by superimposing the three-phase fluxes.

$Ni\alpha = Nia\ (t) + Nib\ (t) \cos 120 + Nic \cos 240$,

$Ni\beta = Nib\ (t) \sin 120 + Nic \sin 240$.

The complex form of the resulting flux space vector's α and β components is,

$Ni\alpha\ (t) + jNi\beta\ (t) = N\ [i\alpha\ (t) + ji\beta\ (t)] = NiR$. where "iR" is the current reference space vector.

$iR = [i\alpha + ji\beta] = iR\ e\ \hat{}jwt$

$VR = [V\alpha + jV\beta] = VR\ e\ (\hat{}jwt+\theta)$

Currently existing space vector produces flow. This current space vector is produced by an analogous voltage space vector. Circular fluctuation is averaged during Pulse Width Modulation (PWM) operation. The average variation space vector tip should trace a circle with a speed that is equal to the input frequency, thanks to the PWM system. For sinusoidal three-phase excitations, the point of the alternating quantity's average space vector moves similarly quickly around a circle.

The eight states' operational conditions are 000, 001, 010, 011, 100, 101, 110, and 111, where 000 and 111 are the same. Other than 000 and 111, all states are the same. The code 000 denotes that the output terminals are shorted to the down switches and that all three down switches are turned on. 111 means that the output terminals are shorted to them and that all three of the top switches are on. Other states besides 000 and 111 are in operation. Any pole with an arrow pointing down or upward implies that the topmost switch is off and the lower switch is open, while the opposite is true for any pole with an arrow pointing downward. Additionally, three-phase voltages expressed as circular resulted in voltage VR. The circular route is broken into six sections to reflect the six active states. The eight potential states between each sector's voltages are V0, V1, V2,….,V7

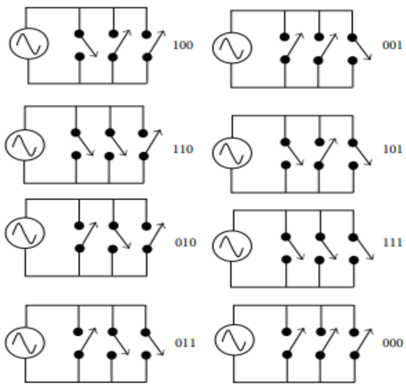

Figure 6. Switching States for the Proposed Matrix Converter [8]

Sampling time period (Ts) is,

$$T_s = (T_0 + T_n + T_{n+1}).$$

where T1, T2, and T0 are the sampling period for the active vectors V1 and V2 and the zero vectors, respectively.

In general, the generated voltage vector's average value is represented as follows:

$$\int_0^{T_s} V_R\,dt = \int_0^{T_0/2} V_0\,dt + \int_{T_0/2}^{T_0/2+T_n} V_n\,dt + \int_{T_0/2+T_n}^{T_0/2+T_n+T_{n+1}} V_{n+1}\,dt + \int_{T_0/2+T_n+T_{n+1}}^{T_s} V_7\,dt$$

The zero vectors (V0 and V7) have zero as their average voltage. The corresponding voltage vector are as follows,

$$(V_R T_s) = \left[V_\alpha + jV_\beta\right] T_s = (V_n T_n) + (V_{n+1} T_{n+1}).$$

where, $\alpha\beta$ is the reference voltage component.

$$\begin{vmatrix} V_\alpha \\ V_\beta \end{vmatrix} T_s$$

$$= \frac{2}{3} V_S \left[\begin{vmatrix} \cos\frac{(n-1)\pi}{3} \\ \sin\frac{(n-1)\pi}{3} \end{vmatrix} T_n + \begin{vmatrix} \cos\frac{(n)\pi}{3} \\ \sin\frac{(n)\pi}{3} \end{vmatrix} T_{n+1} \right],$$

$$\begin{vmatrix} V_\alpha \\ V_\beta \end{vmatrix} T_s = \frac{2}{3} V_S \begin{bmatrix} \cos\frac{(n-1)\pi}{3} & \cos\frac{(n)\pi}{3} \\ \sin\frac{(n-1)\pi}{3} & \sin\frac{(n)\pi}{3} \end{bmatrix} \begin{vmatrix} T_n \\ T_{n+1} \end{vmatrix},$$

where, V_S is the RMS value of the source input voltage ofthe converter and n = 1, 2, 3, . . . represent the sectors.

In terms of $\alpha\beta$ components triggering times for the different sectors are,

$$\begin{vmatrix} T_n \\ T_{n+1} \end{vmatrix} = \frac{\sqrt{3}}{2} \frac{T_s}{V_S} \begin{bmatrix} \sin\frac{(n)\pi}{3} & -\cos\frac{(n)\pi}{3} \\ -\sin\frac{(n-1)\pi}{3} & \cos\frac{(n-1)\pi}{3} \end{bmatrix} \cdot \begin{vmatrix} V_\alpha \\ V_\beta \end{vmatrix}.$$

The corresponding Vα and Vβ components for any given reference space vector V_R can be determined, from which the duration of the active vectors in the pertinent sector can be underside. The remaining position is to differentiate between the available single-phase energy.

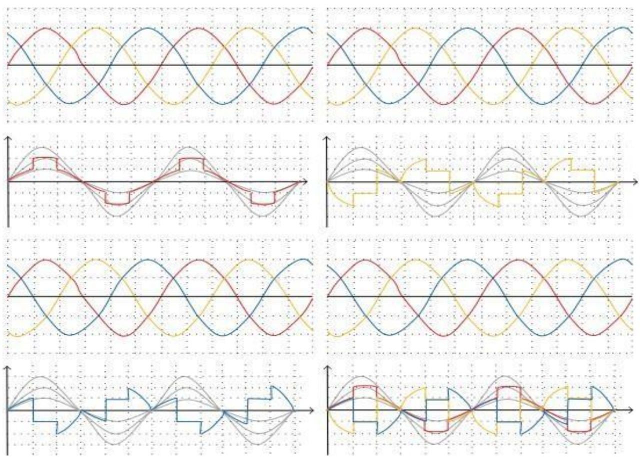

Figure 7. Output Voltage Waveform of SP2TP matrix converter [9]

3. Pulse width Modulation

A. Types of PWM techniques

(i) Sinusoidal Pulse Width Modulation

In the basic application, a high-frequency triangular "carrier" wave is compared to the required reference waveform (modulating sinusoidal signal) to get the correct output voltage.

At the output, the positive or negative input voltage is supplied depending on whether the signal voltage is more or less than the carrier waveform. The average voltage delivered to the load when one triangle wave is proportional to the signal's constant amplitude. The chopped square waveform's low frequency components match the required waveform, while its upper frequency components are near to the carrier frequency. When the modulating signal is a sinusoid of amplitude Am and the triangular carrier is Ac, the modulation index is m=Am/Ac.

This is because the AC voltage waveform's root mean square value is still the same as the input voltage. Tweaklist directs yield voltage abundancy. It is recommended that in three-phase systems, m=fc/fm=3k k€N such that all three waveforms are symmetric. It should be noted that the method works well for m=1. When m>1, the carrier and signal do not cross. It results in overmodulation.

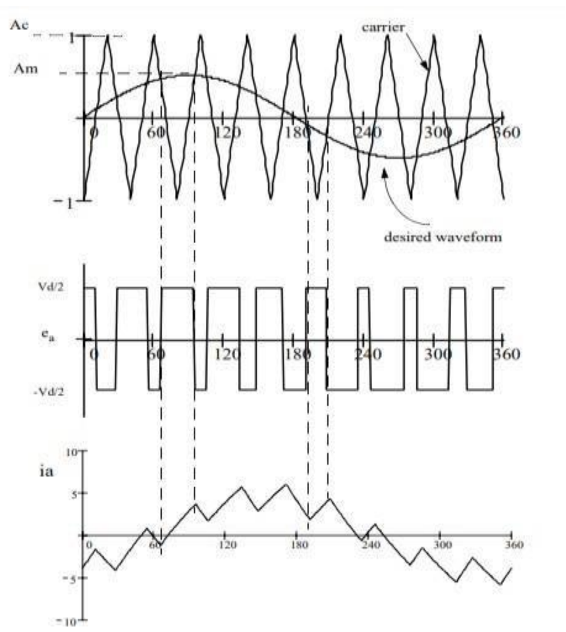

Figure 8. Principal of Sinusoidal Pulse Width Modulation [10]

(ii) Space Vector Modulation Techniques

Space Vector Pulse Width Modulation (SVPWM) is a technique used in the final step of field -oriented control to provide the proper 3-phase voltages to the motor by determining the pulse-width balanced signals for the inverter switches.

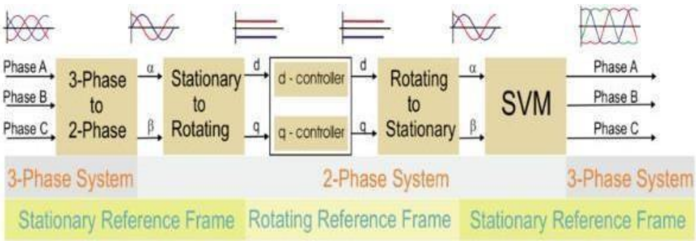

Figure 9. Block Diagram for SVPWM [11]

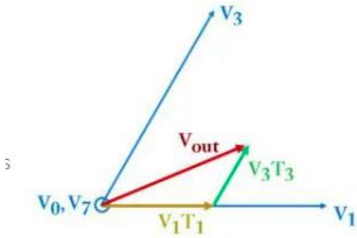

Figure 10. Eight Sector for Space Vector [12]

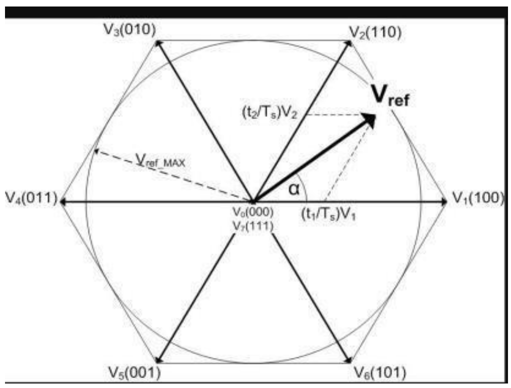

Figure 11. Voltage Reference [13]

Figure 11 shows the Voltage Reference between the Basic Vectors 1 and 3 Switching time for vector 1 and 3.

4. Existing System

A. Block diagram

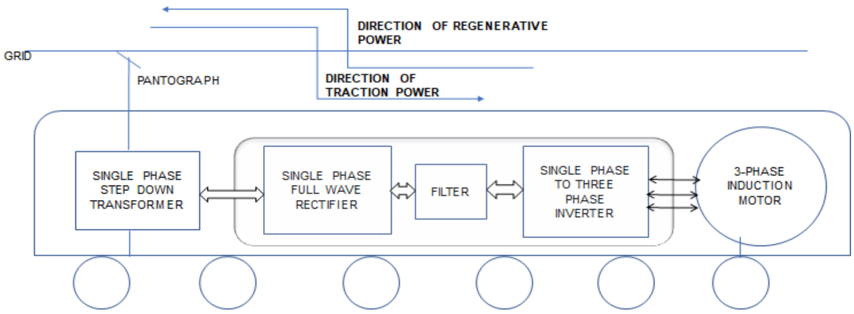

Figure 12. Block Diagram of the Existing System

B. Single Line Diagram

A typical single line diagram for Electric Locomotive shown in the below figure. It helps to study the overview of Electric Locomotive. The below single line diagram shows the electrical connection of the system.

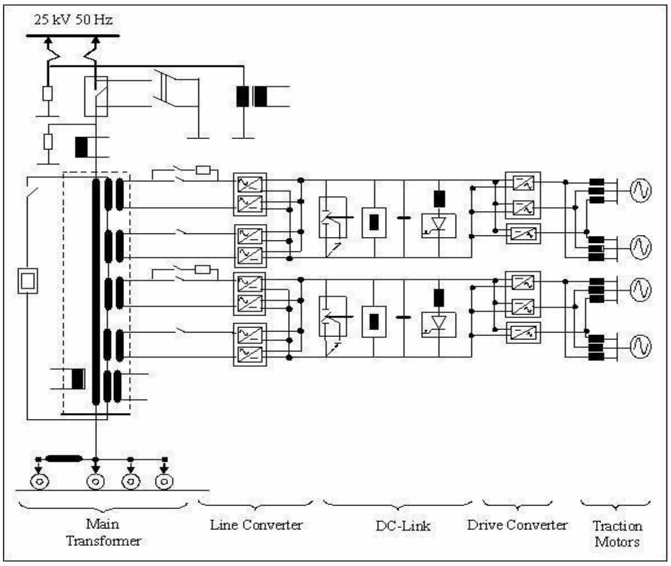

Figure 13. Single Line Diagram of the Existing System [14]

For maximum output RMS,

$$V_{max,RMS} = \frac{V_{DC}}{2} \times \sqrt{3} \times \frac{1}{\sqrt{2}} \times m$$

Resultant output voltage across vector 1 and 3 is,

$$V_{out} = V_1 T_1 + V_3 T_3 + V_0 T_0$$

Where, modulation index(m)=fcarrier/fmodulating signal.

Compared to sinusoidal pulse width modulation, the space vector modulation is a less harmonic component, better efficient, and the output waveform is stepped sinewave.

C. Working

The single line diagram illustrates that AC drawn from Over Headlines which is scaled down with the assistance of transformer. The yield of transformer was transformed into DC through converter and this can be changed over back to three stage AC by inverter. The adequacy of the three stage inverter yield is persistently balanced to control the locomotive's tractive, regenerative braking, and speed. This permits the driving or breaking torque of the footing engines to be persistently balanced, resulting in a smooth move between the driving speeds.

D. Drawbacks

Some of the drawbacks of traction converter are:

- In the presence of more storage element, the converter size was large.
- Poor regenerative braking.
- It contains more switches, therefore switch loss is also increased.
- Because of the existence of a DC link, the heat dissipation is more.

5. Proposed System

A. Block Diagram

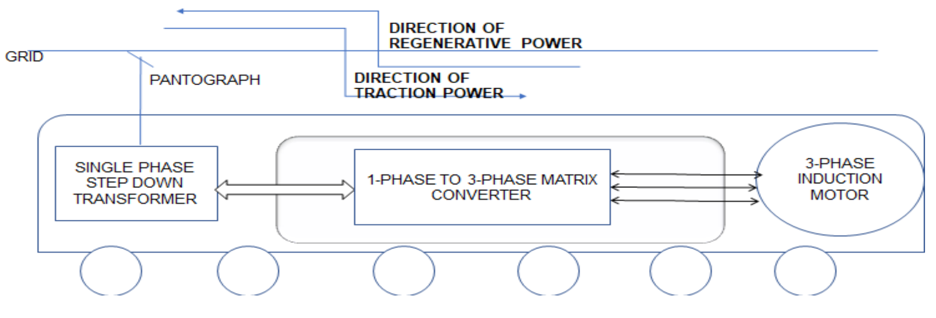

Figure 14. Block Diagram of the Proposed System

The proposed system block diagram shown above represents the outline for conventional electric locomotive which consists of transformer, matrix converter and induction motor.

B. Circuit Diagram

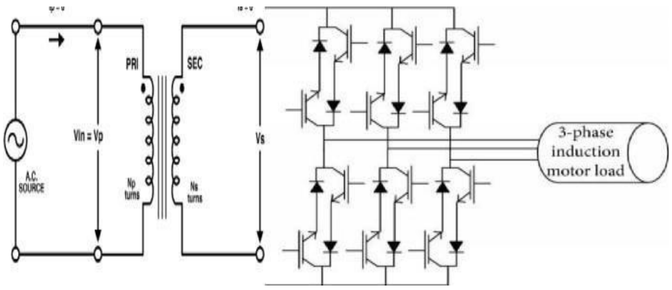

Figure 15. Circuit Diagram of The Proposed System

C. Working

The circuit schematic shows how traction Over Headlines AC is scaled down using a transformer. The transformer output is the fixed AC that is transformed to variable AC via a matrix converter and then back to three phase AC using a single matrix converter. The amplitude of the matrix converter output is continually adjusted by power electronic switches (IGBT switches) to regulate the locomotive's tractive, regenerative braking, and speed. This permits the breaking torque of the induction motor to be continuously adjusted, resulting in a smooth transition between driving speeds.

D. Merits of the SP2TP Matrix Converter

The significant merits of the SP2TP matrix converter are,

- Due to the presence of bidirectional power flow, the regenerative power is quite better compared to the conventional type traction converter.
- Small volume energy-storage devices.
- SP2TP matrix converter is also used for controllable power factor in traction motor.

E. WPA 5 Electric Locomotive Specification

Table 2. Electric Locomotive specification

TRANSFORMER RATING	
Primary Voltage	25000V
Secondary Voltage	2180V
Frequency	50HZ
TRACTION SOURCE	
Nominal Voltage	25000V
Peak Voltage	35350V
Frequency	50Hz
MOTOR SPECIFICATION	
TYPE	DOUBLE CAGE SQIM
Power Rating	1150Kw
Voltage Rating	2180V
Frequency	50Hz

6. Simulation and Results

A. Simulation of the Proposed System

The MATLAB model of the proposed matrix converter is shown below.

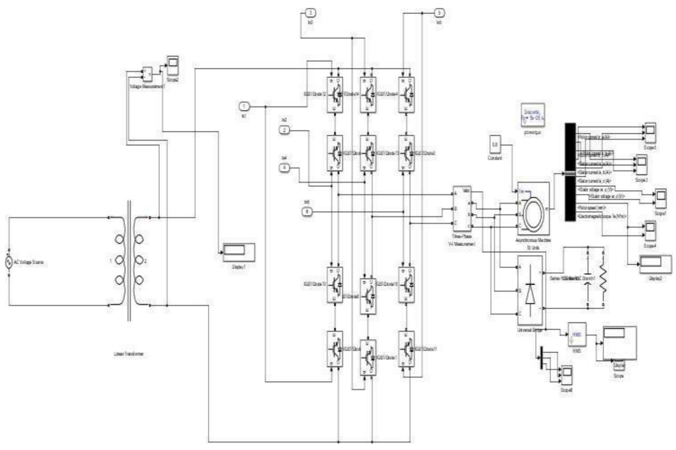

Figure 16. Simulation model of the Proposed System

a. Simulation of SPWM

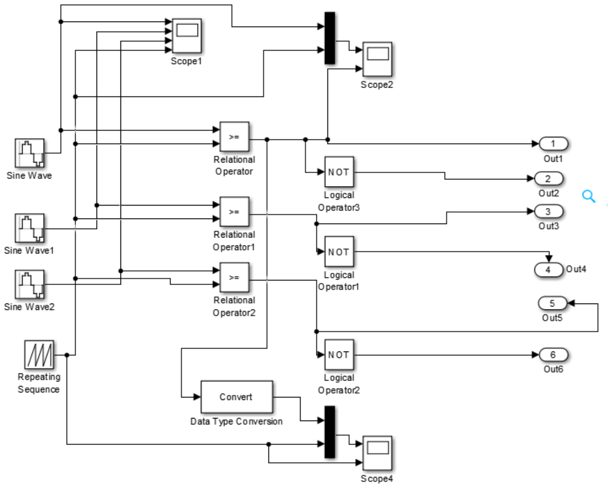

Figure 17. Simulation Model of SPWM

b. Output Results of Proposed System By SPWM Techniques

The below figures 18 to 22 show the output line voltage, stator current, output phase voltage, rotor speed and Total Harmonic Distortion (THD) of the proposed system using SPWM techniques, respectively.

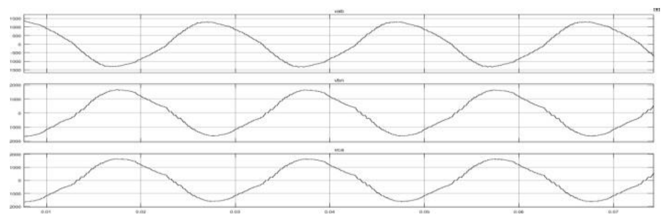

Figure 18. Output Line Voltage of Converter by SPWM

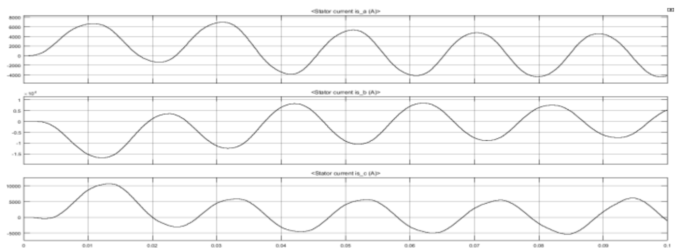

Figure 19. Stator Current of Induction Motor by SPWM Techniques

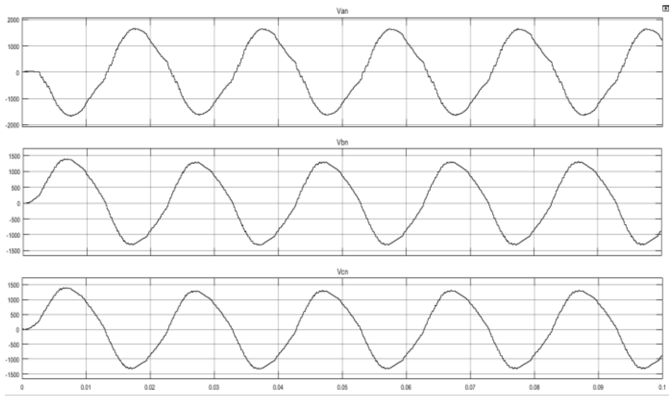

Figure 20. Output Phase Voltage of Induction Motor by SPWM Technique

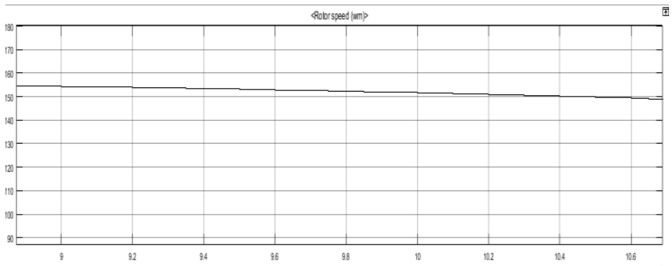

Figure 21. Rotor Speed of Induction Motor by SPWM Techniques

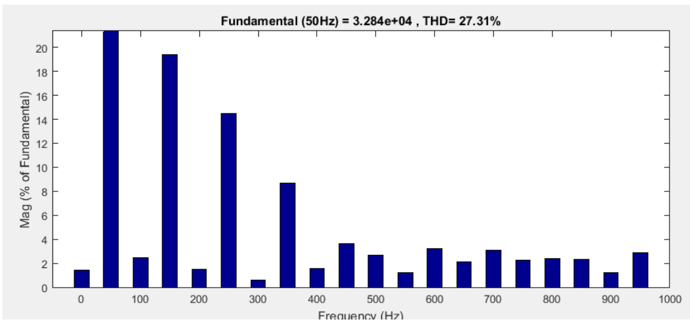

Figure 22. Total Harmonic Distortion of Output Voltage

The THD was more than the IEEE standard. To reduce the total harmonic distortion, space vector PWM techniques are used to analysis the converter.

c. Simulation of SVPWM

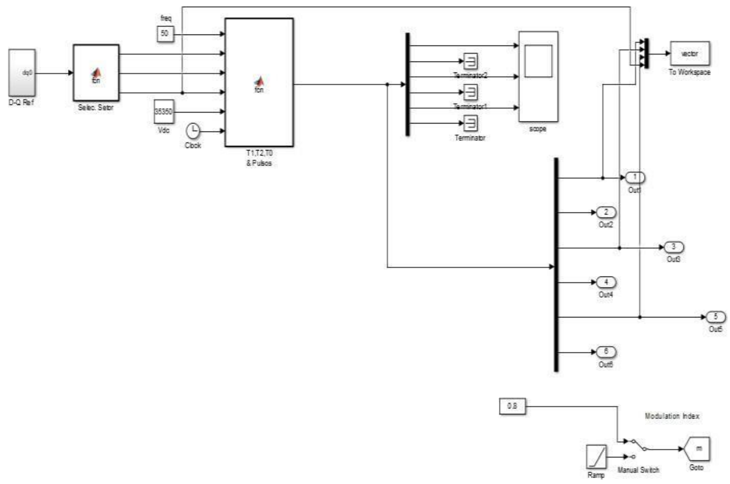

Figure 23. Simulation Model of SVPWM

d. Output Results of the Proposed System by SVPWM Techniques

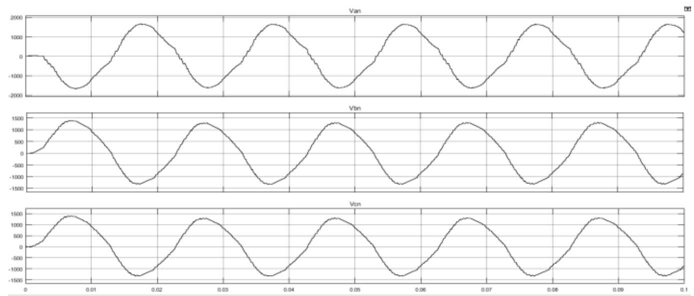

Figure 24. Output Phase Voltage of Converter by SVPWM

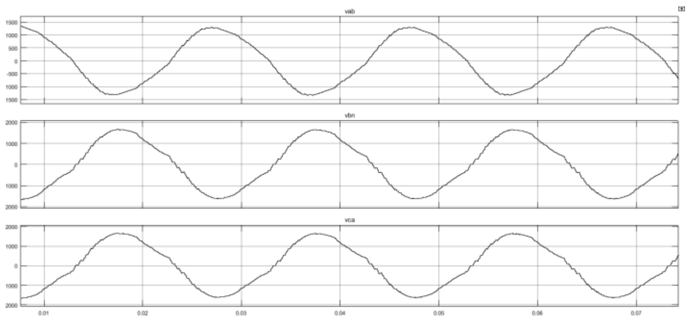

Figure 25. Output Line Voltage of Converter by SVPWM

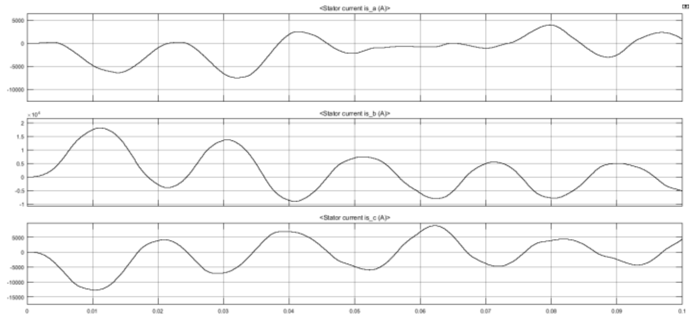

Figure 26. Stator Current of Induction Motor by SVPWM Techniques

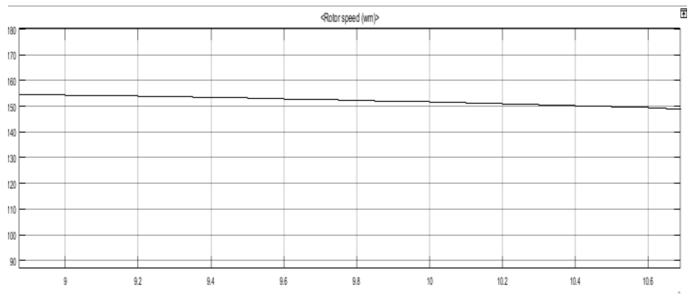

Figure 27. Rotor Speed of Induction Motor by SVPWM Techniques

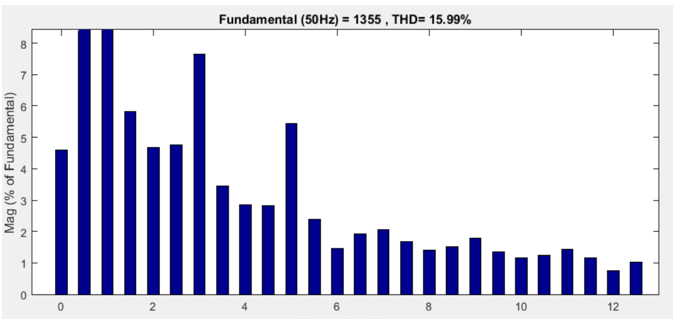

Figure 28. THD of Output Voltage of SVPWM

B. Comparison of PWM Techniques

Table 3. Comparison of PWM Techniques

S.NO	PWM TECHNIQUES	THD %
1.	Sinusoidal PWM	27%
2.	Space Vector PWM	16%

7. Conclusion

The SP2TP Matrix Converter is rising in popularity because of its compact size, user-friendliness, and high level of dependability. The fact that the SP2TP Matrix Converter can be utilised in the already present converter in Electric Locomotive is the major benefit. In addition to this, switching mechanisms are utilised in order to achieve gate triggering control of the matrix converters. SP2TP Matrix Converter reduces the size of typical converters in electric locomotive.

8. Future Scope

The proposed system has a THD of 16%, however the IEEE standard requires that it must be less than 5%. Therefore, there is still space for improvement to boost the converter's overall quality along with the verification of the bidirectional power flow in SP2TP Matrix Converter, which helps to increase the regenerative braking of the electric locomotive.

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