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Analysis of Losses of Propulsion systems on Electric Diesel Rail Trains

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Abstract –*Train is one of transportation which supports the mobilization of society. Futhermore, it is affordable and comfortable so that people prefer using it. One of trains which is usually used by many people is KRDE or electric diesel railway, which is an innovation of technology in PT. INKA based on railway industry. It is one of railway that need electricity as the main source of energy that comes from alternator. it will handle all power of load needs on KRDE like as propulsion and auxiliary load. Therefore, the fluency of KRDE is affected by electrical system of the railway, which is mostly affected by propulsion load because it needs bigger power than auxiliary load. In this research presents about losses calculation on KRDE that are Three- phase rectifier, Variable Voltage Variable Frequency (VVVF) inverter and Three phase induction motor. Three phase rectifier and VVVF inverter will simulated by PSIM software to understand how the circuit work. The results of this research are explain about the number of loss energy in three phase rectifier is 21,6 Watt. In VVVF inverter and three induction motor, there are five samples. From analysis of the samples result that VVVF inverter has the highest efficiency 95,53% with loss energy 19,992 KW, which on 645 Volt about output voltage and 90 Hz about output frequency. In three phase induction motor, 91, 426% is the highest efficiency and it has 18,211 KW at loss energy, which on 635 Volt about input voltage and 36,38 Hz about input frequency. Then, the highest efficiency of propulsion system is 94,59% and 53,38 KW about loss energy, which on 635 Volt about input voltage and 36,38 Hz about input frequency in induction motor.*

Keywords: *KRDE, Propulsion Load, Loss Energy*

I. Introduction

In Indonesia, there is a railroad manufacturing company named PT. INKA (Railroad Industry). Along with the progress of science and technology, PT. INKA has experienced developments in the railroad products it produces so that it becomes a modern railroad manufacturing industry. One result of the development of technological innovation at PT. INKA in the field of railways, namely Electric Diesel Railroad or KRDE. KRDE is a form of railroad that requires electricity as the main energy source that comes from the Alternator. The alternator as a source of electricity in the KRDE serves as a support for the sustainability of electricity in the propultion and auxiliary systems.

In the train propulsion system, the resulting voltage value will affect the rotation speed of the traction motor. The need for a traction motor rotational speed on a train is variable which is based on the situation and condition of the train speed. To get the voltage value in accordance with what is needed, it is necessary to consider the parameters

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that affect it, namely losses or losses in the system. These losses are caused because in the propulsion system there are electric and mechanical forces due to the generator, rectifier, inverter and traction motor components. The relationship between output power and losses is inversely proportional, where the greater the losses that occur in the system, the smaller the power generated. These losses will cause a variety of losses to the system or other equipment, so that if left unchecked will result in low performance efficiency on the train. Therefore, by knowing the magnitude of losses, the efficiency of the system can be known, so that the system is expected not to experience interference when operated.

Based on the above background, a study was carried out on "Analysis of the Losses of the Population System on the Diesel Electric Rail". This study will discuss the losses on KRDE propulsion system components, namely Rectifier, VVVF (Variable Voltage Variable Frequency) Inverter and three-phase induction motor. There are several literature bases used in the preparation of this study. First, research on IGBT losses in the inverter that has been done by Kaixin et al. The study was titled " The IGBT Losses Analysis and Calculation of Inverter for Two-seat Electric Aircraft Application". In this study discussed the losses on IGBT inverters, losses on diode conduction, switching losses, total losses and efficiency. Based on these studies it was found that the efficiency of 95.13% was obtained when the current was 68.31% and 93.42% was obtained when the current was 97.41 A [1].

Second, research on three-phase induction motors was carried out by Isdiyanto. The study was entitled "The Impact of Rotational Changes on the Performance of 3 Phase Induction Motor Phase Cage Rotors". In this study, the efficiency of three phase induction motors is discussed, which is influenced by source voltage, rotation speed and source frequency. The results of this study indicate that the most optimal motor work is obtained when the source voltage is 350 volts and the source frequency is 50 Hz [2].

Finally, research on induction motors that have been done by Suyamto. The study was entitled "Power and Torque Analysis on Induction Motors". In this study discussed the losses, the amount of power and torque on the induction motor. In these experiments three types of experiments were carried out, namely the test without load, load and the rotor was held. From all data obtained from the experiment, we can calculate all the power contained in the motor and torque on the shaft [3].

The purpose of this study is to determine the value of losses as well as the magnitude of the efficiency values for each component contained in the electric diesel Railroad (KRDE) propulsion system.

II. Methods

Flowchart for the research is presented in Fig. 1.

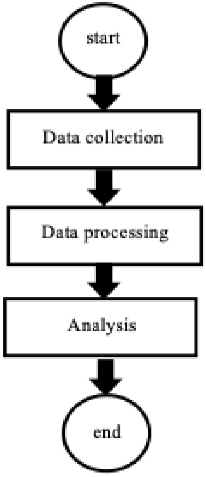


Fig. 1. Flow diagram of research methodology

1. Data collection

In this study data collection was done by collecting data directly and interviews with staff of the Electrical Design section at PT. INKA (Persero).

2. Data processing

After the required data is collected, the next step is data processing. Data processing is carried out in accordance with the objectives of this thesis research and refers to Chapter II. Data to be processed about power losses contained in the propulsion system on the Electric Diesel Railroad (KRDE). This data processing includes components contained in the KRDE propulsion system, namely Generator, three-phase Rectifier, VVVF inverter and traction motor. Processing in the form of calculations refers to the study of literature that has been collected. Furthermore, the working principle of the components will be simulated using PSIM software and the component losses will be calculated based on technical data.

3. Analysis

From the data that has been processed, the next step is to analyze the results that have been obtained. As for matters related to the discussion of loss analysis in the propulsion system are:

a. Analysis of three-phase synchronous generator.
b. Analysis of losses contained in Rectifer.
c. Analysis of losses contained in the inverter VVVF.
d. Analysis of losses contained in the traction motor.

III. Results

III.1. General

In this section we will discuss the calculation of the losses contained in each component of the Electric Diesel Rail (KRDE) propulsion system. The stages of the discussion is presented in Figure 2.

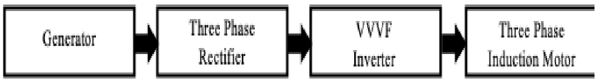


Fig. 2. Schematic Analysis of KRDE Component Sequences

III.2. Locomotives on Electric Diesel Rail Trains

Figure 3 is a locomotive of an electric diesel rail train which uses electric transmission to drive a traction motor. The KRDE locomotive is equipped with a diesel engine and various components that support the smooth running of the train. The locomotive has two boogies with C-C configuration, which are three wheels in each boogie and each wheel is driven by a traction motor. The traction motor will get electrical energy through an inverter that comes from the alternator and has been submitted by the rectifier first.

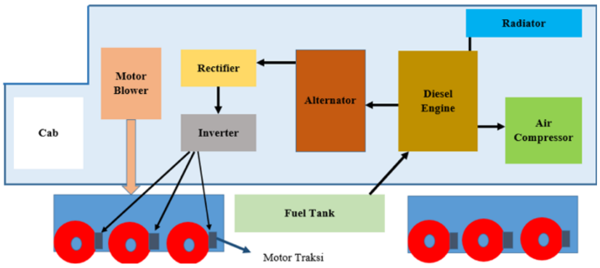


Fig. 3. Locomotive on KRDE

The existence of a blower motor in the picture serves to cool down the rectifier and inverter and is used to regulate the temperature contained in the locomotive room. Meanwhile, to maintain the temperature of the diesel engine, then using a radiator with the aim that the diesel is at the optimal temperature of the engine. Diesel engines are also used as a driving force on air compressors that are used for pneumatic systems. In addition, the locomotive is also equipped with a machinist cabin (cab) which has a steering table (stand control) and a control panel (electronic control). The control panel functions to control rectifiers / inverters, lighting and other related electrical.

III.3. Electric Diesel Rail Train (KRDE) Propulsion System

Electric Diesel Rail Train (KRDE) is a form of railroad that utilizes a diesel engine as a source of electric power. The diesel engine in the electricity of the electric diesel railroad train is used as a prime mover. Diesel engine is a type of engine with internal combustion or called a combustion engine. The diesel engine in the KRDE functions to produce the mechanical energy needed to rotate the rotor on the generator. The KRDE diesel engine is connected to a generator in one shaft to generate electricity. A general schematic drawing of the propulsion system in KRDE is presented in Figure 4.

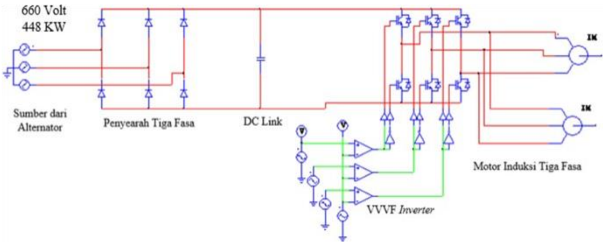


Fig. 4. The general circuit of the propulsion system in KRDE

The output of the generator is alternating electricity (AC) which is used as a three-phase power source for the electrical load contained in the KRDE. To be able to deliver electrical energy to the propultion load, the generator or alternator must first pass through a three-phase rectifier. This three-phase rectifier serves to convert alternating voltage (AC) output from the generator into a direct voltage (DC). The output of the rectifier in the form of direct voltage (DC) will be forwarded to the VVVF inverter to produce a three phase output in the form of alternating voltage (AC) and variable frequency according to the needs of the traction motor in the form of a three phase induction motor.

III.4. Three Phase Synchronous Generator

This section will describe the synchronous generator technical data used in KRDE. Synchronous generator in KRDE is very important in its electricity. That is because the output of the synchronous generator will support the need for electricity sources in various electrical loads in the KRDE. The following are technical data from the synchronous generator on KRDE:

1. Data Specifications

TABLE I
SYNCHRONOUS GENERATOR TECHNICAL DATA

Working Area	Value
Output Power	560 KVA
Output Power	448 KW
Power Factor	0.8
Number of Poles	4
Voltage	660 V
Current	489.87 A
Frequency	60 Hz
Rotation	1800 rpm
Field Current	115 A
Excitation Voltage	167 V
Stator Exciter Obstacles	1.09 Ohm

2. Output Power Calculation

Based on Table I, the power output of the synchronous generator is 560 KVA for apparent power and 448 KW for active power. The following is a calculation of the generator output power based on the data above:

a. Output calculation if calculated based on terminal voltage, current and power factor, the value of the active power generated by the generator is as follows:
$P_{out} = \sqrt{3}$ x V x I x cosf
$P_{out} = \sqrt{3}$ x 660 x 489.87 x 0.8
$P_{out} =$ 448 KW (1)

b. Calculation of the value of output power if calculated based on apparent power and power factor on the generator, then the value of the active power generated by the generator as follows:
$P_{out} =$ S x PF
$P_{out} =$ 560 x 0.8
$P_{out} =$ 448 KW (2)

In the KRDE electrical system, synchronous generator terminal voltage is demanded to work stable in the system. The change in load will cause load currents (I_a) to change as well. These changes will affect the resistance (R_a) and synchronous reactance (X_s) or called synchronous impedance (Z_s). Changes in the load current will also change the value of the voltage induced anchor (E_a) in accordance with the equation $V_t = E_a - I_a (R_a + jX_s)$. Therefore, in order for the terminal voltage to remain stable it is necessary to set the induced voltage (E_a). Meanwhile, the induced voltage can be adjusted by adjusting the number of revolutions (n) and magnetic fluxes (ϕ).

Setting the number of revolutions involves the initial drive, because the rotor speed is rotated by using mechanical energy. Whereas the regulation of magnetic flux will involve excitation which gives a DC (V_f) voltage to the field coil. Excitation voltage in a closed circuit will cause a DC current (I_f). The field coil flowing DC current will produce a flux which will rotate when the rotor is rotated by the prime mover, resulting in the arising of GGL at the anchor due to the fluctural alignment that drives the anchor coil. The existence of an excitation source that supplies direct field current (DC) in the field coil in the rotor will cause a direct current flowing in the field coil. This current will result in losses in the rotor coil resulting in heat.

The magnetic flux produced by the rotor coil is not completely covered by the stator coil. In other words, that the stator coil has a leaky fluk which is stated by the armature resistance (R_a). In addition, with the load attached to the synchronous generator output, the armature current will immediately flow (I_a) so that it will cause losses to the stator in the form of heat. Therefore, to calculate the amount of losses contained in synchronous generators must know the value of the parameters R_f and R_a.

III.5. Three Phase Rectifier

In KRDE Rectifier or rectifier electrical system functions to continue the output of the generator in the form of alternating voltage (AC). The output voltage of the genarator is a type of AC three-phase voltage which will be rectified to be a DC voltage. In this section, the working principle of the three-phase rectifier will be simulated using PSIM software. This rectifier circuit uses a full wave rectifier with the main components in the form of diodes totaling six pieces. A series for three-phase rectifier is presented in Figure 5.

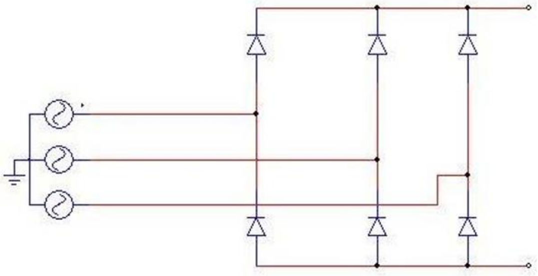
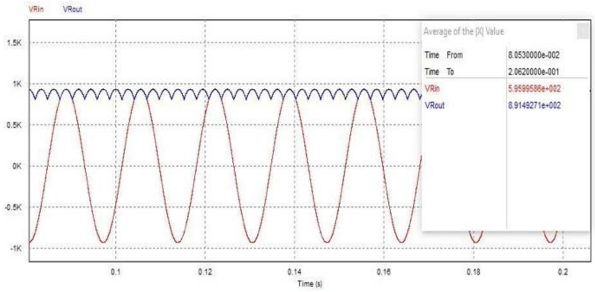


Fig. 5. Three-phase rectifier circuit

Figure 5 is a general description for three-phase rectifier as a function of the rectifier in the electrical system in KRDE. The rectifier uses a three-phase voltage input of 660 Volts which is the output of a synchronous generator. The three phase rectifier with six diodes used in the circuit is a type of full wave surrender that will work by rectifying all sine wave cycles. Therefore, two diodes will continue to deliver to produce a complete DC output path. Diodes with mostly positive cathode voltages will be delivered. Diodes with negative voltages will also be delivered. This is because the bridge type rectifier will change either half positive or half negative from AC voltage to DC. In this full wave rectifier will produce denser waves because it is a combination of a positive signal cycle and a negative signal cycle. Therefore, the rectifier will still output at the mountain and valley periods from the sine signal.

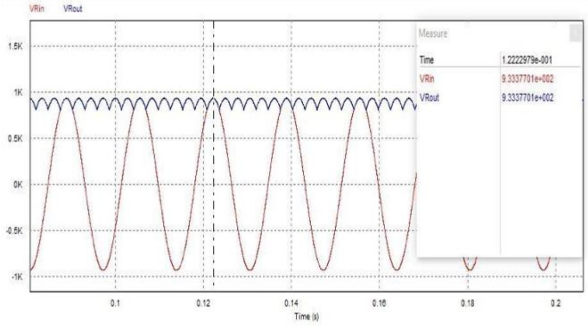
1. Three Phase Rectifier Output Voltage

The working principle is displayed based on the simulation results of the circuit in Figure 4. The simulation results of the series is presented in Figures 6 and 7.



```
Time  From    8.0530000e-002
Time  To      2.0620000e-001
VRin          5.9599586e+002
VRout         8.9149271e+002
```

Fig. 6. Vdc wave Three-phase rectifier



```
Time          1.2222979e-001
VRin          9.3337701e+002
VRout         9.3337701e+002
```

Fig. 7. DC peak voltage waveform

Based on the results of the three-phase rectifier simulation in Figures 6 and 7, explains that the VRin wave in the form of a sine wave is the directional input voltage. Meanwhile, VRout is the output wave from rectifier that has been rectified. In addition, the simulation results in Figure 5 state that the rectifier output voltage is 891 Volts. Meanwhile, the peak voltage of the rectifier produces 933 volts. If proven based on theory, then as follows:

a. Average voltage of rectifier

$$V_{dc} = (3\sqrt{2} / \pi) \text{ x } V_{in}$$
$$V_{dc} = 1.35 \text{ x } 660$$
$$V_{dc} = 891\text{Volt} \quad (3)$$

b. The peak voltage of the rectifier

$$V_{peak} = \sqrt{2} \text{ x } V_{in}$$
$$V_{peak} = 1.414 \text{ x } 660$$
$$V_{peak} = 933.3 \text{ Volt} \quad (4)$$

Based on the above calculation results, proving that the rectifier output voltage value between the calculation results with the simulation results is the same as 891 Volts for the average voltage and 933 Volts for the voltage the peak.

2. Loss on Three Phase Rectifier

TABLE II
DIODE DATA SHEET

Primary Characteristics	
$I_{F(AV)}$	3.0 A
V_{RRM}	50 V, 100 V, 200 V, 300 V, 500 V, 600 V, 800V, 1000V
I_{FRM}	200 A
I_R	5.0u A
V_F	1.2 V

Based on Table II, the power output of the synchronous generator is 560 KVA for apparent power and 448 KW for active power. The following is a calculation of the generator output power based on the data above:

The calculation of losses from the three-phase rectifier is as follows:

a. Losses on diode

$$P_{diode} = V_f \text{ x } I_f$$
$$P_{diode} = 1.2 \text{ x } 3$$
$$P_{diode} = 3.6 \text{ Watt} \quad (5)$$

b. Total losses of rectifier

$$P_{\text{losstot}} = 6 \text{ x } P_{loss}$$
$$P_{\text{losstot}} = 6 \text{ x } 3.6$$
$$P_{\text{losstot}} = 21.6 \text{ Watt} \quad (6)$$

c. Rectifier output power

$$P_{rect} = P_{in} - P_{losstot}$$
$$P_{rect} = 448000 - 21.6$$
$$P_{rect} = 447.978 \text{ KW} \quad (7)$$

d. Rect in efficiency

$$\eta = (P_{rect} / P_{in}) \text{ x } 100\%$$
$$\eta = (447.978 / 448) \text{ x } 100\%$$
$$\eta = 99.99\% \quad (8)$$

The losses to the rectifier are as presented in

Table III.

TABLE III
LOSSES ON THE THREE-PHASE RECTIFIER

Working Area	Value
V input	660 V
P input	448 KW
V output	981 V
Power Loss	447.978 KW
Efficiency	99.99%

3. Filter Capacitors

In KRDE electricity, there is a DC link component after the rectifier component. This is because when viewed from Figure 6 the output waveforms of the three-phase rectifier, it appears that the waves have not produced pure DC voltage. In these waves there are still a number of AC voltages mixed with DC voltages or called ripples or ripples. Therefore, to suppress the ripple on the rectifier by adding a filter in the form of a capacitor used as a voltage rectifier. A three-phase rectifier circuit using a capacitor and its output simulation results is presented in Figures 8 and 9.

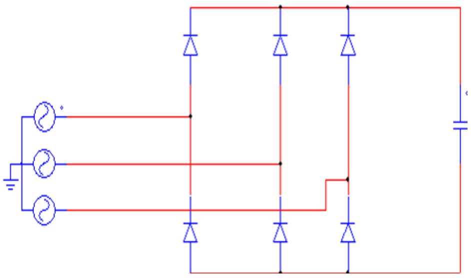
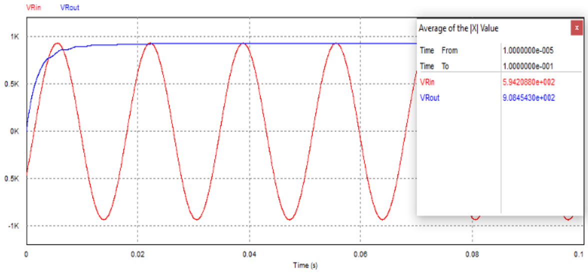


Fig. 8. Rectifier circuit using a filter



Time From	1.0000000e-005
Time To	1.0000000e-001
VRin	5.9420880e+002
VRout	9.0845430e+002

Fig. 9. Results of a rectifier simulation after adding a filter

In Figures 8 and 9, it can be seen that adding a filter capacitor to the rectifier circuit makes the ripple of the output waveform suppressed. So that after the addition of the capacitor, the output of the three-phase full-wave rectifier becomes flat or in accordance with the direct voltage (DC). In addition, after the addition of the capacitor filter the output voltage approaches the peak voltage, which is 933.3 Volts with a relatively pure unidirectional voltage waveform. This is because adding a capacitor that is paralleled with the load, the voltage ripple will be greatly suppressed because the capacitor can store energy. Filter capacitors in rectifiers work by charging energy when the diode is conduction, whereas it releases energy when the diode is not conduction. When the conduction diode the capacitor fills quickly to near the peak voltage. Thus the load will continue to get energy when the diode is not conduction. This is because the capacitor serves as a storage area that receives energy at peak loads and supplies energy to the load when the output rectifier is low.

III.6. VVVF (Variable Voltage Variable Frequency) Inverter

This section will discuss the VVVF Inverter on the Electric Diesel Rail (KRDE) propulsion system. VVVF Inverter is a type of three-phase inverter that has a variable voltage and frequency. The input voltage of the inverter is in the form of a direct voltage (DC) originating from the Three-phase rectifier, which is 933.3 Volts. Direct voltage (DC) will then be converted to produce AC voltage. By using the switching technique on the frequency inverter it can also be changed to get the desired motor speed.

The control switch in the inverter in this discussion uses the PWM (Pulse Witdh Modulation) technique because it can regulate variable voltage and frequency. The main component used as a switch in this discussion is in the form of a semiconductor component, namely IGBT. The output from VVVF is then used to rotate an AC traction motor that requires variable frequency and voltage values. A general series of three-phase inverters that act as VVVF inverters is presented in Figure 10.

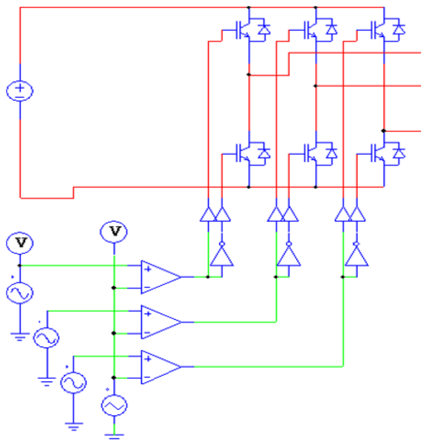


Fig. 10. VVVF Inverter Circuit

In this discussion an analysis of losses will occur in the VVVF inverter. There are five different conditions based on load requirements for voltage and frequency. Therefore, in each circumstance it will have different voltage and output frequency values.

The losses on this inverter consist of two types, namely diode losses consisting of conduction losses and IGBT losses consisting of conduction losses and switching losses. Conduction losses on inverters that use PWM are affected by the duty cycle, while for switching losses are affected by the switching frequency. Based on the IGBT datasheet of BSM 200 GA DN2, the parameters of IGBT are as presented in Tables IV and V.

TABLE IV
PARAMETERS OF LOSSES ON IGBT

Parameter	Symbol	Values
Colector-Emitter Saturation Voltage	V_{ge}	15 Volt
	I_c	200 A
	$V_{ce(sat)}$	5,3 Volt
	T_j	125°C
E_{ON}	V_{cc}	1200 Volt
	V_{ge}	15 Volt
	I_c	200 A
	R_{gon}	6,8 Ohm
E_{OFF}	V_{cc}	1200 Volt
	V_{ge}	-15 Volt
	I_c	200A
	R_{goff}	6,8 Ohm

TABLE V
DIODE LOSS PARAMETER ON THE INVERTER

Primary Characteristics	
I_F	2.1 A
I_F	200 A
V_{ge}	0
T_j	125 ℃

Based on Tables V and VI, the losses on the inverter VVVF are as follows:

a. Conduction loss

$P_{cond} = V_{ce(sat)} \times I_c$

$P_{cond} = 5.3 \times 200$

$P_{cond} = 1060$ Watt (9)

b. Eon loss

$E_{on} = (V^2 / R)$

$E_{on} = (V^2 / R)$

$E_{on} = (15^2 / 6.8)$

$E_{on} = 33.088$ Watts (10)

As for the magnitude of the switch when on is 0 Volts, because in the data Table IV, it is noted that Vge = -15 V or voltage negative so that means IGBT withstand current. While the losses from the diode based on the datasheet as follows:

$P_{diode} = V_f \times I_f$

$P_{diode} = 2.1 \times 200$

$P_{diode} = 420$Watt (11)

Then the total loss of the diode on the inverter VVVF, as follows:

$P_{totdiode} = 6 \times 420$

$P_{totdiode} = 22.52$ KW (12)

Following are five states for analyzing losses on an Inverter VVVF is presented in Table VI.

TABLE VI
FIVE STATES OF LOAD REQUIREMENTS

P_{in} (KW)	V_{out} (V)	f (Hz)	I_{pk} (A)
444.978	645	90	231.511
	635	36.38	235.209
	493.9	28	302.285
	321	18,2	456.19
	160.5	9	930

In this section an analysis of the losses of a three-phase inverter will be used using a switching frequency of 500 Hz.

In the first state the inverter output will be set to get an output voltage of 645 volts and a frequency of 90 Hz. The output will then be used to rotate the motor with a rotation speed of 2634 rpm. The simulation results are as presented in Figure 11.

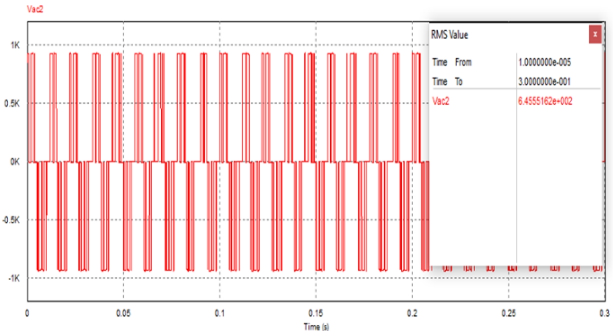


Fig. 11. VVVF output waveform of the inverter when state 1

To get a voltage of 645 volts at the inverter output, the circuit uses a modulati index of:

$D = (A_r / A_c)$

$D = (2.28 / 4)$

$D = 0.57$ (13)

So that the losses which occurs in the VVVF Inverter as follows:

a. Dissipation loss

$P_{cond} = P_{cond} \text{ x } D$

$P_{cond} = 1060 \text{ x } 0{,}57$

$P_{cond} = 604.2 \text{ Watt}$ (14)

b. Loss of switch

$$P_{sw} = \frac{(E_{on} + E_{off}) \text{ x } I_{pk} \text{ x } f_{sw} \text{ x } V_{dc}}{\pi \text{ x } I_{nom} \text{ x } V_{nom}}$$

$$P_{sw} = \frac{33.088 \text{ x } 231.511 \text{ x } 500 \text{ x } 933.3}{\pi \text{ x } 290 \text{ x } 1700}$$

$P_{sw} = 2.308\text{KW}$ (15)

c. Total losses

$P_{igbt} = 6 \text{ x } (P_{cond} + P_{sw})$

$P_{igbt} = 6 \text{ x } (0.604 + 2.308)$

$P_{igbt} = 6 \text{ x } 2.912$

$P_{igbt} = 17.472 \text{ KW}$

Then,

$P_{totloss} = P_{igbt} + P_{totdiode}$

$P_{totloss} = 17.472 + 2.52$

$P_{totloss} = 19.992 \text{ KW}$ (16)

d. Output power

$P_{out} = P_{in} - P_{igbt}$

$P_{out} = 447.978 - 19.992$

$P_{out} = 427.506 \text{ KW}$ (17)

e. Efficiency

$\eta = (P_{out} / P_{in}) \text{ x } 100\%$

$\eta = (427.506 / 447{,}978) \text{ x } 100\%$

$\eta = 95.43\%$ (18)

For the calculation of losses in the second to fifth circumstances can be seen in appendix 1. By using the same method as in the calculation of losses in the first state, the losses in the VVVF Inverter are as presented in Table VII.

TABLE VII
LOSSES AND EFFICIENCY IN VVVF INVERTER

Working Area	Condition				
	1	2	3	4	5
P_{in} (KW)	447.978				
D	0.57	0.547	0.225	0.106	0.029
Volt (V)	645	635	494	321	160
f (Hz)	90	36.38	28	18.2	9
Power Loss (KW)	19.992	20.07	22.026	50.502	58.302
P_{out} (KW)	427.586	427.908	425.952	397.476	389.676
Efficiency (%)	95.53	95.51	95.08	88.73	87.55

Based on the Table VII, if a graph is made of the duty cycle relationship with the inverter output voltage, as presented in Figure 12.

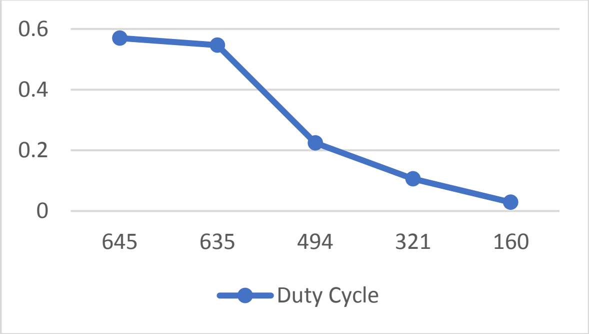


Fig. 12. Graph of the relationship between D and Vout

Figure 12 above states that the relationship between duty cycle and output voltage is directly proportional. In the inverter VVVF, the duty cycle is a comparison between the reference voltage and the carrier voltage. By comparing the two voltages, you will get the output voltage as desired. The amount of output voltage on the inverter, will determine the losses that occur on the inverter itself. If a graph is made, the relationship between the output voltage and the inverter VVVF losses is as presented in Figure 13.

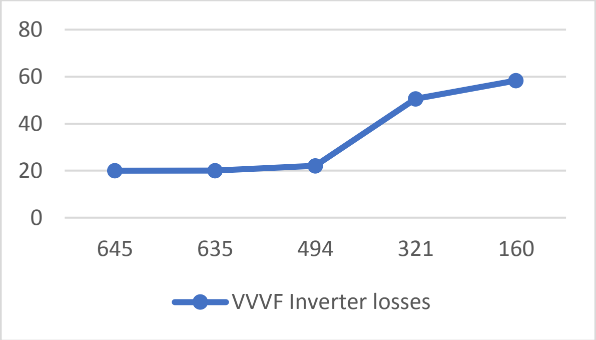


Fig. 13. Graph of the relationship between the output voltage of the inverter and losses

After knowing the amount of losses that occur in VVVF Inverter, we obtain an efficiency as presented in Figure 14.

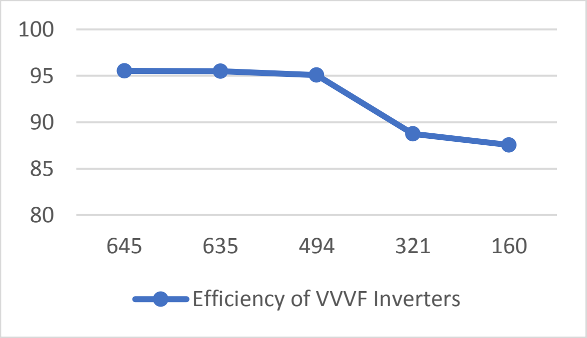


Fig. 14. Graph of inverter efficiency against losses

III.7. Three Phase Induction Motor

This section will discuss the losses on the three-phase induction motor. This induction motor acts as a traction motor in KRDE as the prime mover. This motor gets a voltage supply from the VVVF Inverter in the form of a variable voltage and frequency to be converted into mechanical energy as needed. However, in the process of converting electrical energy into mechanical energy there are losses that occur in the engine so that the input from the VVVF inverter is not completely converted. The losses contained in the three-phase induction motor are stator copper losses, stator core losses, copper rotor losses, friction and wind losses and others. Therefore, this section will discuss the losses on the three-phase induction motor used in the Electric Diesel Rail (KRDE) propulsion system so that the efficiency of the engine is obtained. In the discussion of the losses contained in the traction motor, it is divided into two parts. The first discussion is about the comparison of losses on the motor using five different conditions. While the second discussion about the ratio of losses when the motor has the same input voltage, but has a different slip value.

TABLE VIII
TECHNICAL DATA OF THREE PHASE INDUCTION MOTOR IN THE FIRST STATE

Working Area	Values	Working Area	Values
Pshift	200 KW	X1	0.52286 Ohm
Voltage	645 Volt	X2	0.24223 Ohm
Frequency	90 Hz	Xh	0.24223 Ohm
Current	197.28 A	Φg	14.32132 mVs
Rotating	2634 rpm	L1	0.921 mH
Moment	740 Nm	L2	0.422mH
Cos phi	0.87	Lh	25.326 mH
Efficiency	93.44%	Rc	667.490 Ohm
Friction Power	2331.44 Watt	R1	0.04581 Ohm
10	25.09 A	R2	0.04080 Ohm

Based on Table VIII, the losses on the induction motor are as follows:

1. Motor input power
   $P_{in} = \sqrt{3} \times V \times I \times \cos\theta$
   $P_{in} = \sqrt{3} \times 645 \times 197.28 \times 0.87$
   $P_{in} = 191.74 \text{ KW}$ (19)
2. Stator copper losses
   $P_{ts} = 3 \times I_s^2 \times R_s$
   $P_{ts} = 3 \times 197.28^2 \times 0.04581$
   $P_{ts} = 5.349 \text{ KW}$ (20)
3. Stator core losses
   $P_i = ((3 \times E_s^2) / R_c)$
   $P_i = (3 \times 645 / 667.490)$
   $P_i = 1.870 \text{KW}$ (21)
   So that the total losses of the stator
   $P_s = P_{ts} + P_i$
   $P_s = 5.349 + 1.870$
   $P_s = 7.219 \text{ KW}$ (22)
4. Rotor power = air gap power
   $P_{cu} = P_{in} - P_s$
   $P_{cu} = 191.74 – 7.219$
   $P_{cu} = 184.521 \text{ KW}$ (23)
5. Rotor loss
   $N_s = (120f / p)$
   $N_s = (120 \times 90) / 4$
   $N_s = 2700$ (24)
   Then the magnitude of the slip
   $s = (N_s - N_r) / N_s$
   $s = (2700 – 2634) / 2700$
   $s = 0.024$ (25)
   So that the losses on the copper rotor
   $P_{tr} = s \times P_{cu}$
   $P_{tr} = 0.024 \times 184.521$
   $P_{tr} = 4.428 \text{ KW}$ (26)
6. Mechanical power
   $P_{mek} = P_{cu} - P_{tr}$
   $P_{mek} = 184.521 - 4.428$
   $P_{mek} = 180.093 \text{ KW}$ (27)
7. Friction loss
   $P_g = 2331.44 \text{ W}$ (28)
8. Stray loss
   $P_b = 1.5\% \times (P_{mek} - P_g)$
   $P_b = 1.5\% \times (180.093 – 2.33144)$
   $P_b = 2.666 \text{ KW}$ (29)
9. Total losses
   $P_{Losses} = P_{ts} + P_i + P_{tr} + P_g + P_b$
   $P_{Losses} = 5.349 + 1.870 + 4.428 + 2.33144 + 2.666$
   $P_{Losses} = 16.644 \text{ KW}$ (30)
10. Power output
    $P_{out} = P_{mek} - P_g - P_b$
    $P_{out} = 180.093 – 2.33144 – 2.666$
    $P_{out} = 175.096 \text{ KW}$ (31)
11. Efficiency
    $\eta = (P_{out} / P_{in}) \times 100\%$
    $\eta = (175.096 / 191.74) \times 100\%$
    $\eta = 91.319\%$ (32)

In the same way as in the above calculation, the value of losses and efficiency in the three induction motor using variations of the input as presented in Table IX.

Table IX states that each state of the induction motor has a different rotation speed. The difference in rotational speed of the rotor on the induction motor is caused by the presence of different voltage values. If seen from the Table IX, the voltage will be proportional to the rotational speed. That is because the voltage received by the stator will affect the coupling. The decrease in coupling received by the rotor will result in motor rotation speed will also decrease in accordance with the voltage drop. Coupling in a three-phase induction motor is an interaction between two dynamic magnetic fields, namely the stator magnetic field and the rotor magnetic field. The rotor's magnetic field originates from the induction voltage which is caused by the cutting of the rotor coil by the stator rotating field. A graph is presented in Figure 15.

TABLE IX
DATA ON THREE PHASE INDUCTION MOTOR LOSSES

Working Area	Condition				
	1	2	3	4	5
P_{in} (KW)	191.7	212.4	165.9	111	59.8
Volt (V)	645	635	493.9	321	160.5
Current (A)	197.2	217.6	217.9	224.4	247.6
Power Loss (KW)	16.6	18.2	16.5	15.1	16.4
P_{out} (KW)	175.1	194.1	149.3	95.9	43.4
Efficiency	91.3	91.4	90	86.4	71.5

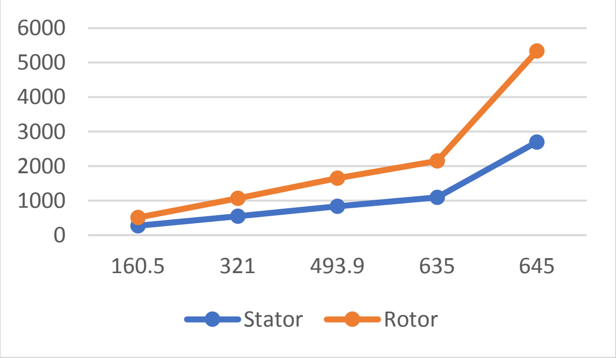


Fig. 15. Voltage relationship graph with motor speed

In addition, the above calculation also results in a different stator rotation value which is directly proportional to the frequency used. When the induction motor uses a frequency of 36.38 Hz, it produces a rotation of 1091 rpm. When an induction motor uses a frequency of 90 Hz it produces a rotation of 2700 rpm. When the induction motor uses a frequency of 28 Hz, it produces a rotation of 840 rpm. When the induction motor uses a frequency of 18.2 Hz, it produces a rotation of 546 rpm. Finally, when the induction motor uses a 9.1 Hz frequency, it produces a rotation of 273 rpm. This is consistent with the theory which states that the magnitude of the rotational speed of the induction motor's magnetic field is influenced by the frequency of the source entering the motor through the stator coil. The amount of rotation in the stator will be directly proportional to the frequency of the source. Based on the relationship between frequency and stator rotation in the above calculation, then if a graph is made as presented in Figure 16.

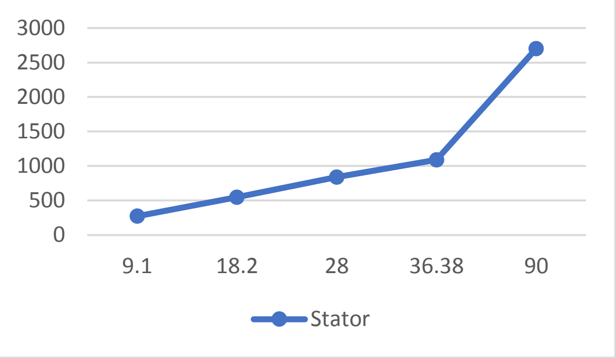


Fig. 16. Graph of frequency relationship with stator speed

In a three-phase induction motor, the rotation of the stator magnetic field will always be followed by the rotation of the induction motor rotor. The existence of friction and wrapper on the rotor will cause the rotor rotation to decrease. In addition, the load will also be 273 546 840 1091 2700 0 500 1000 1500 2000 2500 3000 9.1 18.2 28 36.38 90 Rotational speed of rotor (rpm) Frequency (Hz) Rotating Speed of Stator Rotating Speed affects the rotation of the rotor, where the heavier the load the rotor speed will also decrease. This will result in a difference in rotational speed between the stator and the rotor or slip. Slip on the induction motor is shown in the graph of the relationship between motor voltage and rotation. Meanwhile, the relationship between slip and rotor rotation can be seen in Figure 17.

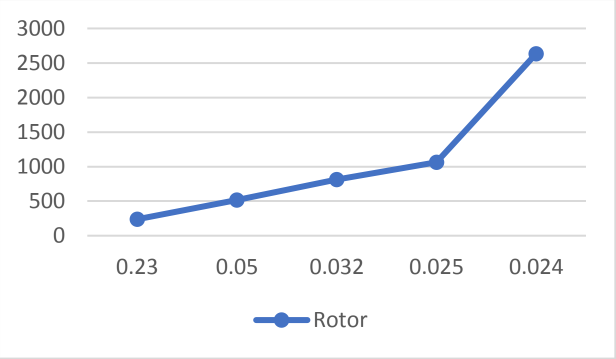


Fig. 17. Graph of slip relationship with rotor rotation

Based on the calculation of the induction motor losses above, slip greatly affects the amount of losses generated by copper rotor. The slippage causes the electrical power to be converted into reduced mechanical power. In addition, the calculation also says that the slip value is inversely proportional to the source frequency. The greater the frequency of the source, the slips produced will be smaller and vice versa. The statement was proven by observations of the five conditions of three phase induction motors. When the source frequency is 90 Hz, the slip is 0.024, when the source frequency is 36.38 Hz, the slip is 0.025, when the source frequency is 28 Hz, the slip is 0.032, when the source frequency is 18.2 Hz, the slip is 0.05, and when the frequency is 0.23 Hz then slip 0.13. This is in accordance with the theory which states that the source frequency is inversely proportional to slip or fr = s.f. The relationship between slip and source frequency and the effect of slip on induction motor losses are presented in Figures 18 and 19.

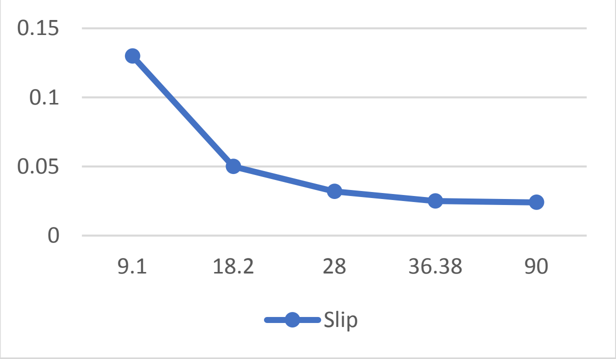


Fig. 18. Graph of source frequency relationship with slip

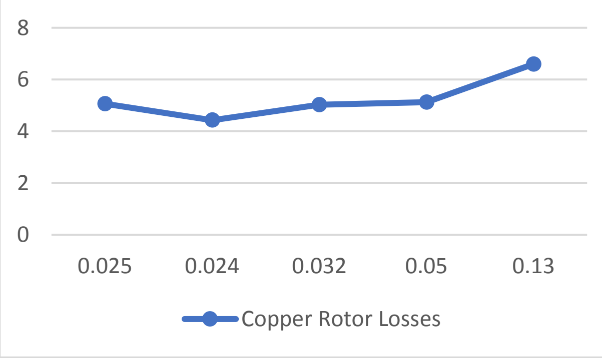


Fig. 19. A graph of the relationship between copper rotor and slip losses

In addition, one of the causes of losses in the induction motor increases is the current. The relationship between current and losses in stator copper is presented in Figure 20.

In addition, one of the causes of losses in three-phase induction motors is the existence of friction losses which are caused by mechanical energy from the rotor. Based on experimental data of the five conditions of the traction motor, the amount of friction loss is directly proportional to the rotor rotation. A graph is presented in Figure 21.

After knowing the value of losses in each part of the three-phase induction motor, then used to determine the value of the efficiency of the three-phase induction motor engine. Based on the above calculation, the efficiency in each condition is as presented in Figure 22.

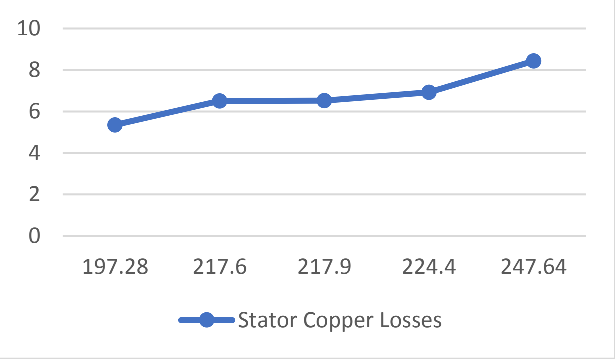


Fig. 20. Graph of the relationship of source current with stator copper losses

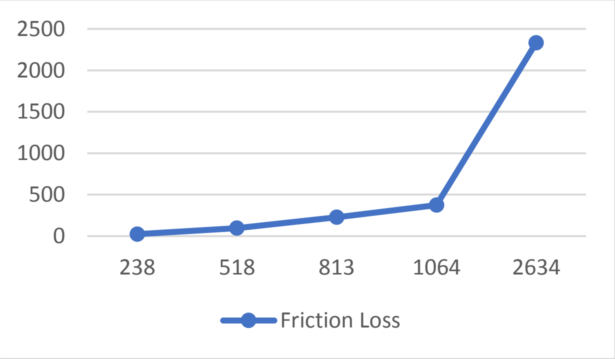


Fig. 21. Graph of the relationship between rotor rotation with friction loss

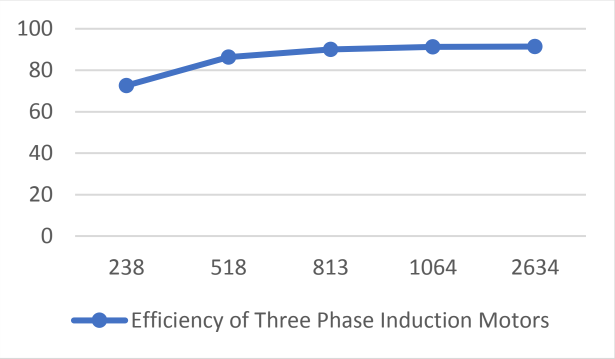


Fig. 22. Induction motor efficiency graph

Based Figure 22, the efficiency states that the efficiency of the three phase induction motor which is used as a traction motor has the highest efficient value at 1064 rpm. In these conditions, the induction motor requires a voltage of 635 volts and a current of 217.6 volts. This means that the motor will work well if used in these circumstances. In addition, the observational data above also states that operating a motor using a low speed will have an impact on engine efficiency.

III.8. Losses and Efficiency of Propulsion Systems

After knowing the value of losses in each component of the propulsion system, it can be seen the value of output power and efficiency in each of these components as presented in Table X.

TABLE X
OVERALL POWER OF PROPULSION SYSTEM COMPONENTS

Input (KW)	Pout Rectifier (KW)	Pout Inverter (KW)	Pout Induction Motor (KW)
448	447.978	430.428	194.764
		430.506	175.096
		428.472	149.605
		399.996	95.147
		392.196	43.47

Because in this discussion there are two motors in one inverter where each motor is assumed to have the same loss value. The total losses from the propulsion system as presented in Tables XI and X.

TABLE XI
LOSSES OVERALL COMPONENTS OF THE PROPULSION SYSTEM

Input (KW)	PLosses Rectifier (KW)	PLosses Inverter (KW)	PLosses M1 (KW)	PLosses M2 (KW)	Total (KW)
448	21.6	19.992	18.235	18.235	56.484
		20.07	16.644	16.644	53.38
		22.026	16.537	16.537	55.122
		50.502	15.893	15.893	82.31
		58.302	16.423	16.423	91.17

TABLE XII
OVERALL EFFICIENCY OF PROPULSION SYSTEM COMPONENTS

Input (KW)	eff Rectifier (%)	eff Inverter (%)	eff M1 (%)	eff M2 (%)	Total (%)
448	21.6	95.53	91.32	91.32	94.54
		95.51	91.43	91.43	94.59
		95.08	90.03	90.03	93.78
		88.73	86.39	86.39	90.38
		87.55	72.58	72.58	83.18

IV. Conclusion

Based on the results of simulations and analyzes that have been carried out, the conclusions from the research on the losses of the propulsion system on the Electric Diesel Rail (KRDE) can be concluded as follows:

1. The synchronous generator functions as an alternating power plant used as a supplier of loads contained in the Electric Diesel Rail Train (KRDE) producing a power of 448 KW and a voltage of 660 Volts.
2. The efficiency value in the three-phase rectifier, which is 99.99% with losses of 21.6 W. In addition, the addition of bank capacitors to the rectifier will suppress the voltage ripple so that the output voltage is equal to the peak voltage, which is 933.3 Volts.
3. VVVF Inverter is a power electronic device that functions to convert DC voltage into AC voltage which has variable frequency and voltage values. Based on the above analysis states that the efficiency value of VVVF is influenced by the switching frequency of the inverter. The results of the VVVF analysis with 500 Hz switching frequency have losses of 19,992 KW and 95.53% efficiency when producing a voltage of 645 volts and a frequency of 90 Hz. Losses of 20.07 KW and 95.51% efficiency are produced when the output voltage is 635 Volts with a frequency of 36.38 Hz. Losses of 22,026 KW and efficiency of 95.08% are generated when the voltage is 493.9 Volts with a frequency of 28Hz. Losses of 50,502 KW and efficiency of 88.73% were generated when the voltage was 321 Volts with a frequency of 18.2 Hz, while losses of 58.302 KW and 87.55% efficiency were generated when the voltage was 160.5 volts with a frequency of 9 Hz.
4. The three-phase induction motor on the Electric Diesel Rail Train (KRDE) functions as the main component in the train propulsion system. Based on the results of the above analysis, it states that the magnitude of the losses on the three-phase induction motor consist of stator losses, rotor losses, friction losses, and other losses. The results of the analysis stated that losses were obtained at 16,644 KW with an efficiency of 91,319% when the input power was 191.74 KW. When the input power is 212.4 KW, losses are 18.211 KW with an efficiency of 91.426%. When the input power is 165.9 KW, losses are 16.537 KW with an efficiency of 90.032%. When the input power is 111.04 KW, the losses are 15.108 KW with an efficiency of 86.394%. When the

input power is 59,893 KW, losses are 16,423 KW with an efficiency of 72,579%.

5. Based on the analysis of the total propulsion system losses above, that the highest efficiency occurs in the second condition, which is 94.59% with losses of 53.38 KW which occurs when the motor input voltage is 635 Volts with a frequency of 36.38 Hz

Acknowledgements

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