ASSESSMENT OF ELECTRIC PROPULSION APPLICATION IN LIGHT RAIL TRANSIT (LRT)

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ABSTRACT

In this paper, one of the most important parts of self-propelled vehicles is presented, namely the Light Rail Transit (LRT), especially the propulsion system. LRT is already operating in several major cities in the world, but in Indonesia its construction has just been completed and is currently operating in Palembang, South Sumatra, and Greater Jakarta area (Jakarta-Bogor-Depok-Bekasi). The methodology used to describe and analyse the LRT propulsion system begins by first reviewing the literature on the development of LRT-type mass transportation in developed countries, then a study of technological developments is carried out on each component of the propulsion system, especially for the propulsion of rail facilities. One of the main components of the LRT-type rail propulsion system that will be used and developed in Indonesia is the VVVF inverter, which functions to regulate the speed of the traction motor which is designed to work in a certain frequency range, for example between 0 Hz to 70 Hz. The VVVF inverter output is controlled by a very popular principle used in railways, namely the constant V/f setting technique. The initial start of the LRT requires high torque to overcome train resistance and to accelerate in a few minutes. To meet these needs while still paying attention to energy savings, the traction power (traction effort) is adjusted, which is the power needed to move the train from a speed of 0 km/hour to 30 km/hour. Traction power is adjusted by varying the frequency to control the speed, the terminal voltage is also varied so that the ratio of the constant V/f constant is maintained at 15.7 V/Hz. The maximum torque of the motor becomes constant at every speed change.

Keywords: Traction motor; V/f control; VVVF inverter.
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INTRODUCTION

The propulsion system is a very important part of self-propelled vehicles such as the Light Rail Transit (LRT), and has become one of the fastest growing types of rail-based vehicles in major cities of the world. As of 1999, around 350 LRT systems were in operation worldwide. LRT and tram systems operate in 388 cities worldwide, mostly in Europe with 206 systems, of which Germany and Russia alone have 123 systems. Furthermore, there are 93 systems in Eurasia, Asia 41 systems and North America 36 systems. Altogether, the LRT carries around 13.6 billion passengers annually (45 million daily) [1]. Other regions such as the Middle East, North Africa and Asia are developing new infrastructure rapidly [1]. The LRT, which is growing rapidly in the world, has also begun to be introduced in Indonesia, among others the ones that are currently built and developed in Palembang and in the Greater Jakarta area (Jakarta-Bogor-Depok-Bekasi). LRT is a light rail vehicle that uses a high-voltage electric propulsion system, 750 V dc. The propulsion system uses an electric motor as a traction motor, which gets its electrical energy supply through an overhead line called a pantograph or through a third rail.

In fact, the LRT propulsion system is in principle identical to the propulsion system for electric rail trains (KRL) that have been used in the Greater Jakarta area (Jakarta-Bogor-Depok-Tangerang-Bekasi).

The KRL propulsion system operated in the Greater Jakarta area uses a traction motor in the form of a three-phase induction motor. Some of the main components of the propulsion system on the KRL are (1) Pantograph as an electricity supplier from the Upstream Electricity Center (PLAA) to KRL, (2) VVVF

IGBT (insulated gate bipolar transistor) inverter as a single-phase DC power converter into three-phase AC power, and as motor speed controller by varying the input voltage and motor frequency [2].

The KRLs that are operated in the Greater Jakarta area using the propulsion system as described above, some are produced in Indonesia and some have been used in other countries and then modified in Indonesia. The KRL, both manufactured in Indonesia and modified in Indonesia, use a propulsion system that is fully imported from other countries.

The construction of LRT (Light Rail Transit) in Palembang as well as in Jakarta, Bogor, Depok and Bekasi, marks a new chapter in Indonesia's transportation system. Before the LRT was developed, the self-propelled trains in Indonesia were the Diesel Electric Rail Train (KRDE) and the Electric Rail Train (KRL), not a type of light rail train. LRT is one of the mass transportations models that is well known in several countries, but is still new in Indonesia. For ensuring its success, this new phase of rail-based transportation requires the attention from engineers and researchers, including experts in technology transfer, technology development and technology adjustment, especially in the propulsion system.

LRT PROPULSION SYSTEM

The LRT which will be developed in Indonesia uses an electric propulsion system similar to that of being built and operated in Palembang, South Sumatra, which consists of 3 train units for 1 LRT series, namely 2 motor car (MC) trains which are placed each at the front and rear, and 1 trailer (T) train in the middle, as can be seen in **Figure 1**, in which the MC train is equipped with a traction motor as part of the propulsion system to drive the wheels of the train, while the T train is not equipped with a traction motor [3].

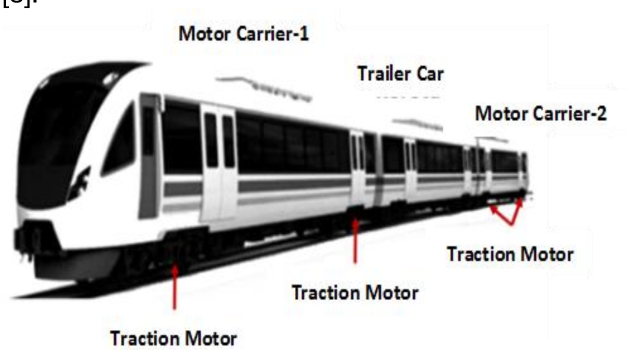

Figure 1 LRT Series (modify by author)

Figure 2 shows a propulsion system for each MC train. Direct current electricity as the driving power is obtained from a power source outside the train in the form of a 750 V dc electric power source via the third rail. Furthermore, the direct current electric power is converted into a three-phase alternating current electric power whose output voltage and frequency can be varied through a device called a VVVF (variable voltage and variable frequency) inverter [4].

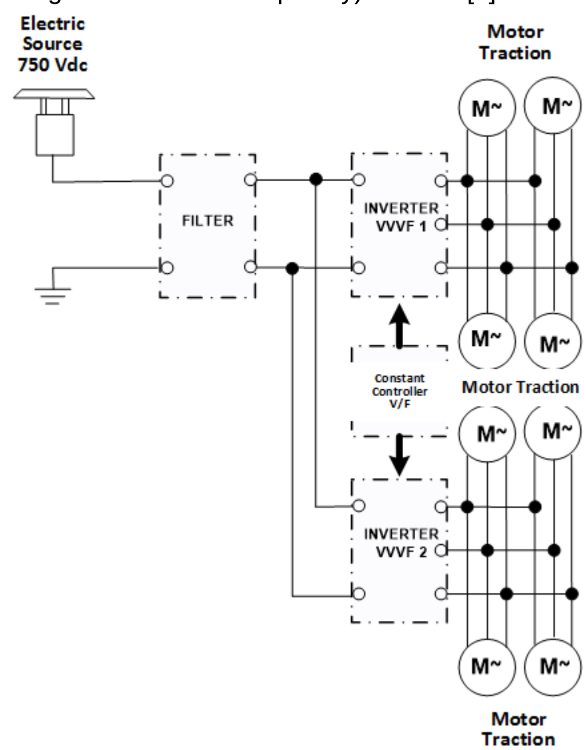

Figure 2 LRT Propulsion System (modify by author)

The VVVF inverter used to regulate the speed of the traction motor is designed to work in a certain frequency range, for example between 0 to 70 Hz. Induction motor speed control which is very popularly used, especially in its use as a traction motor on railway facilities, is a constant V/f adjustment technique, which has several advantages, including:

a. providing a good speed range,
b. providing a good performance,
c. having low initial requirements, and
d. having a wider and more stable operating area.

Basically, the technique of controlling the speed of an electric motor with a constant V/f principle using a VVVF inverter will give better results if the control is not carried out using hardware programming but using software programming. It can be concluded that the key technologies in the LRT propulsion system are

VVVF technology, induction motor technology with a certain frequency range and software-based constant V/f control technology.

The methodology used to describe the LRT propulsion system begins with an exploration and literature search on the development of LRT-type mass transportation in developed countries, including the development of its propulsion system to determine the basic components of the LRT propulsion system. Then, a study was conducted to determine technological developments regarding each component of the propulsion system, especially for the propulsion of railway facilities. In the final stage, the results of the search and study are analyzed, illustrated and concluded.

CHARACTERISTICS OF PROPULSION'S MAIN COMPONENTS

Traction Motor

With the development of inverter technology, especially the VVVF (variable voltage and variable frequency) inverter, the use of induction motors as traction motors is increasingly widespread, including traction motors on LRT. General form of induction motor as a traction motor on the LRT is shown in **Figure 3**.

The start of LRT or other vehicles requires high torque to overcome train resistance and to increase speed which lasts several minutes, for urban or suburban trains. Traction motors must also be capable of dynamic, or regenerative braking, which causes the motor to function as a generator which can provide a considerable advantage by sending electrical energy back to the supply network. Furthermore, all traction motors experience vibration and can have an impact on its components such as brushes and others [5].

To meet these needs, one of the concerns is the traction power (tractive effect), which is the power needed to move the train from a speed of 0 km/hour to 30 km/hour. The tractive effort multiplied by the speed gives the horse power required for the train to reach the maximum allowable speed.

Figure 3 illustrates the design of the power settings given to the LRT for speed control/regulation. When the LRT starts to move, the power exerted is maximum and constant (graphs A-B) up to a certain speed, generally between 30 km/h to 50 km/h. This gives a constant acceleration as well, therefore, the speed of the LRT in that time period increases linearly. Point B is the point of maximum power supply to enter the next period. In the next period, the applied force is reduced gradually through exponential reduction (B-C graph), and the speed increases exponentially towards the maximum speed (C-D) and remains as shown in **Figure 4**, where the characteristics of the expected change in speed function of time from the torque setting are shown, as in **Figure 3**. If the LRT speed setting is designed only in 3 levels, then the speed setting can be done as illustrated in **Figure 5**.

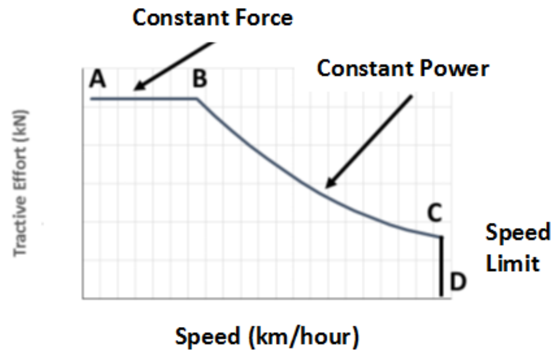

Figure 3 Force vs speed characteristic design (modify by author)

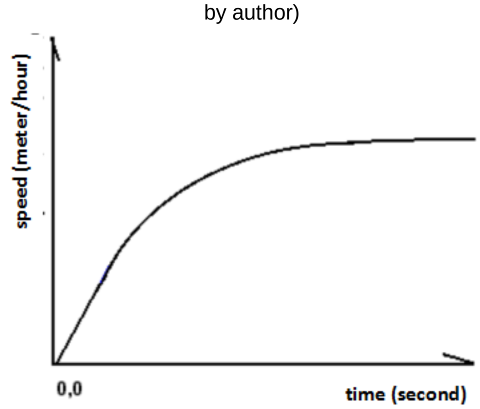

Figure 4 Speed change characteristic (modify by author)

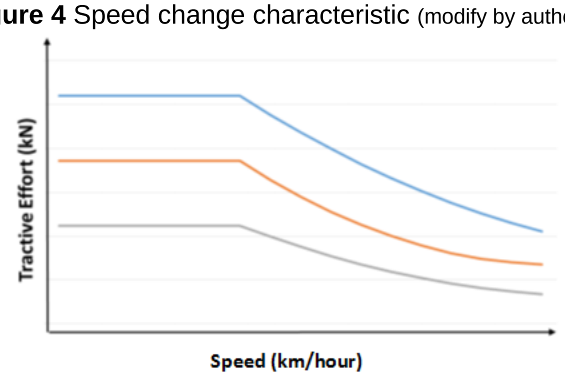

Figure 5 Force vs 3-level speed characteristic design (modify by author)

Furthermore, if the induction motor used as a traction motor is given a constant input voltage with a constant frequency, then its characteristics are shown as in **Figure 6**.

When an induction motor is run from stop to full speed, it produces back-emf, low power factor, high starting current, and the motor continues to draw more active power during acceleration. The consequence is that the starting current is almost constant throughout most of the run-up period, but the power factor continues to increase until the motor speed reaches 80% of full speed, the torque reaches its highest point and the current begins to decrease with a little 'slip'. The torque of the induction motor depends on the quadratic of the applied voltage, therefore the induction motor is very sensitive to any voltage drops at its terminals, so that the induction motor which is designed to work only on one frequency, for example at the 50 Hz frequency, faces difficulties in controlling its speed, because there are only two variable inputs on the induction motors, namely the amount of the input voltage and the frequency of the input voltage.

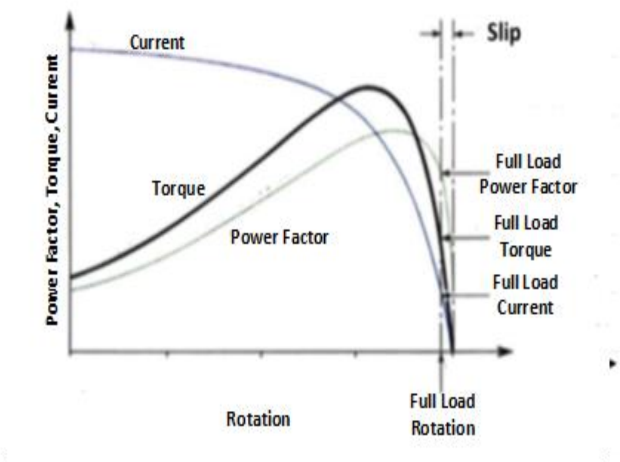

Figure 6 3-phase induction motor characteristic (modify by author)

The speed of an induction motor can actually be varied by varying the synchronous or slip speed for a given load. Meanwhile, the synchronous speed can be varied by changing the frequency of electricity power or the number of poles. The synchronous speed of an induction motor is given in the following equation:

$$N = 120f/P \quad (1)$$

where:
N = rotor speed in rpm
f = voltage supply frequency
p = number of poles

Based on equation (1), changing the input frequency will shift the torque vs speed characteristics as shown in **Figure 7**, which are grouped into two characteristics, namely:

a. Torque vs speed characteristics at speeds below standard, for example between 0 rpm to 1500 rpm by increasing the voltage and frequency linearly.
b. Torque vs speed characteristics at speeds above standard, for example between 1500 rpm to 3500 rpm by increasing the frequency at a constant voltage.

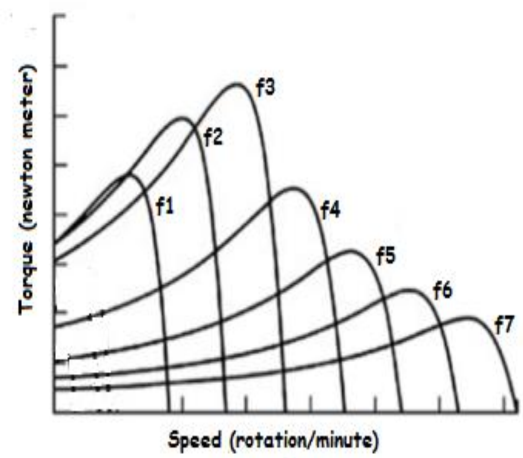

Figure 7 Torque vs speed characteristics of various frequencies (modify by author)

As numerical illustration, a traction motor taken from reference [6] is used to drive a series of LRT 4 x 4 induction motors with the specifications of each motor as follows.

- Output voltage : 0 until 1100 Vac.
- Frequency : 0 until 70 Hz.
- Output power : 180 kW.
- Motor's rotation : 2000 rpm.
- Torque : 1500 Nm

VVVF Inverter

Inverter is an equipment that functions to change/convert direct current (DC) electricity into alternating current (AC) electricity, in which the voltage and frequency can be adjusted as needed. The output voltage is obtained by varying the alternating current (Vac) voltage and maintaining constant inverter gain; or maintaining direct current (Vdc) voltage and varying the gain of the inverter using pulse-width-modulation (PWM) control to obtain a variable output voltage. The inverter gain is defined as the ratio of the ac output voltage to the dc input voltage [4].

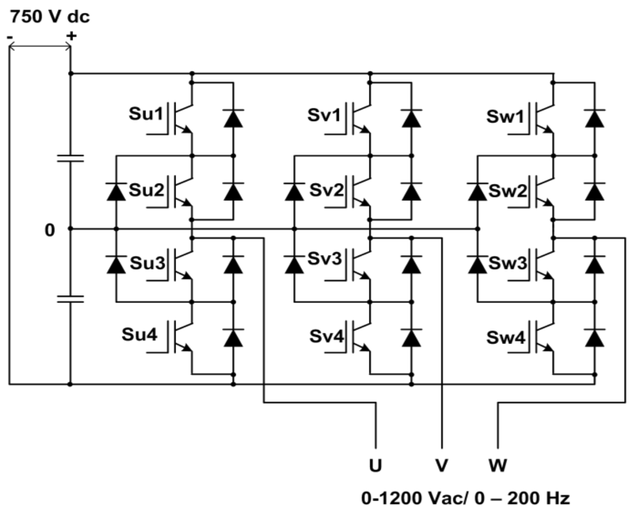

Figure 8 Three-level VVVF inverter [4]

Theoretically, the motor speed can be controlled simply by varying the frequency as shown in **Figure 7**. However, it is advisable to control the amplitude of voltage and frequency of the voltage, as excessive current can flow into the motor at low motor speeds, causing mechanical damage; and also, efficiency decrease. Therefore, the inverter that should be used is a variable voltage and variable frequency (VVVF) inverter as shown in **Figure 8** [4].

The main component that is widely used in VVVF inverter technology for railway propulsion systems including LRT, is the IGBT (insulated gate bipolar transistor). However, high speed IGBT switching increases high frequency leakage current, bearing current and shaft voltage. This also contributes to the problem of voltage reflection which results in high voltages at the motor terminals, especially when the motor is more than 20 meters away from the VVVF inverter.

To overcome this problem, a three-level drive called the Neutral Point Clamped three-level inverter has been introduced as shown in **Figure 8**.

Each phase has four switching devices (IGBT) connected in series. In phase U for example, the circuit works in the following way. When IGBT Su1 and Su2 are turned on (on), the U output is connected to the positive (+) input rail. When Su2 and Su3 are active, it is connected to the midpoint (0) of the bus, and when Su3 and Su4 are active, it is connected to the negative rail (-). Thus, the output can take three voltage values compared to two values in a conventional two-stage system. The relationship between the IGBT status and the resulting output voltage with respect to the dc midpoint is summarized in **Table 1**.

Table 1 Operational Relation between IGBT status and output voltage [4]

	IGBT				Vu
STATUS	Su1	Su2	Su3	Su4	
	On	On	Off	Off	½ Vu
	Off	Off	On	On	-½ Vu
	Off	On	On	Off	0 Vu

Traction Motor Speed Control

In the induction motor speed control using the constant V/f control principle, the motor speed is controlled by the amount of stator voltage and the frequency can be adjusted so that the flux in the air gap can be maintained at the desired value and steady state. Such a control principle is also called scalar control because it focuses only on steady-state dynamics.

Synchronous speed can be controlled by varying the frequency of the supply voltage (input). The voltage induced in the stator is proportional to the product of the flux in the air gap and the frequency of the input voltage ($E \propto \Phi f$). If the stator voltage drop is negligible, then the motor input voltage is proportional to the product of the flux in the air gap and the frequency of the terminal voltage input voltage ($V \propto \Phi f$). Thus, the frequency will decrease without changing the supply voltage and this will cause an unwanted increase in air gap flux. Therefore, whenever the frequency is varied to control the speed, the terminal voltage is also varied to maintain V/f ratio constant, the maximum torque of the motor becomes constant at each speed change.

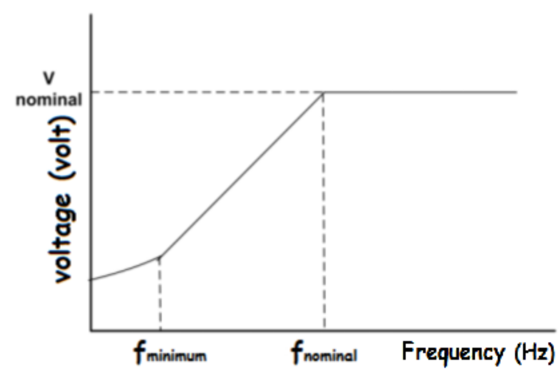

Figure 9 Characteristic of Voltage-frequency V/f controller for traction motors [7]

In **Figure 9**, the characteristics of the V/f control voltages for the traction motor are given with 3 (three) control areas, namely:

a. Frequency ranges from 0 to the minimum frequency. At these frequencies, the stator voltage versus the stator frequency characteristic is not linear. This is because at lower frequencies, the stator resistance becomes comparable or even greater than the stator leakage reactance, thereby reducing the flux in the air gap significantly. This reduces the torque generated.
b. Area between the minimum frequency and the nominal frequency. In this area, it is possible to control the motor speed with the principle of constant V/f.
c. Area with a frequency greater than the nominal frequency. In this area, the control that can be done is using a decreased V/f.

Based of above explanation, V/f constant control can work for:

a. Controlling so that stator V voltage and stator F frequency are changed by maintaining the ratio (V/f) constant under all operating conditions.
b. A constant ratio (V/f) ensures a constant flux in the air gap, and therefore, a constant torque. This type of control has the advantage of producing a constant torque from start to nominal speed.
c. Obtaining maximum torque during operation until reaching nominal speed, V/f ratio is adjusted with $V_{nominal}/f_{nominal}$.
d. Above the nominal frequency, the constant stator voltage is equal to the nominal stator voltage.
e. When the V/f ratio decreases, the flux in the air gap also decreases. The torque generated by the motor decreases but the output power remains constant.

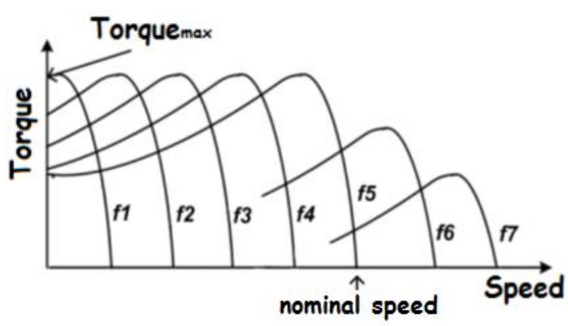

Figure 10 Characteristic of torque-speed V/f controller for traction motors [7]

If the above conditions are illustrated in the form of a control characteristic graph using the constant V/f control principle, it will look like in Figure 10, where it can be seen that the voltage and frequency reach their maximum values at the nominal speed. It can also be observed in Figure 10 that the frequency:

$$f_1 < f_2 < f_3 < f_4 < f_5 < f_6 < f_7 \quad (2)$$

CONSTRUCTION OF LRT PROPULSION SYSTEM

Based on the description above and referring to **Figures 1** and **Figure 2**, an LRT propulsion system can be constructed, which consists of three trains in one series. The first train and the last train are Motor Car (MC) trains, which are equipped with a propulsion system to drive LRT trains with the principle as given in **Figure 11**, where it can be seen that 750 Vdc high-voltage electric power is obtained from distribution substations via third rails. By using the Current Collector Device (CCDV), electrical energy is supplied to the MC train from the third rail. Furthermore, electric power from the High Voltage (dc) Box is channeled to 2 VVVF inverter units to be converted into three-phase alternating current with an output voltage that moves from 0 V to 120 Vac with a frequency from 0 Hz to 200 Hz. The output of each VVVF inverter becomes the output of 4 induction motors, each, with a capacity of 180 kW and a maximum rotation of 2000 rpm. The speed of the traction motor is controlled by adjusting the voltage and output frequency of the VVVF inverter using a constant V/f controller. The velue of V/f constant is taken from the ratio between $V_{nominal}$ and $f_{nominal}$ of the traction motor, which is 1100 V/70 Hz = 15.7 V/Hz.

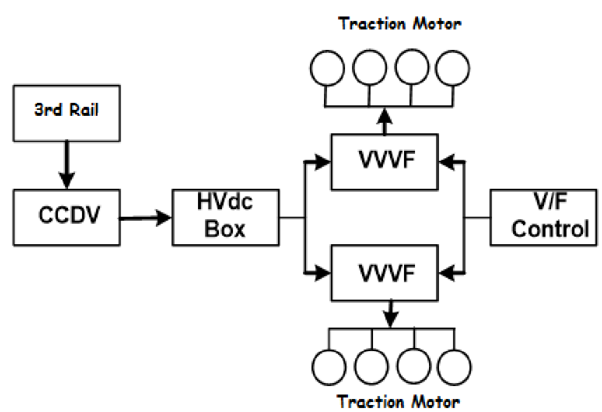

Figure 11 Working principle of LRT propulsion system (modify by author)

If the speed of the traction motor is set to only 3 levels, namely 40%, 70%, and 100% as shown in **Figure 5**, then the output voltage and frequency are set as shown in **Table 2**.

Table 2 Traction motor speed control

	V Output (Vac)	Frequency (Hz)
Full speed	1100	70
70% of speed	770	49
40% of speed	440	28

The above-mentioned practical operation of the propulsion system is a combination of the four states which can be described as follows:

- Soft acceleration in purely motorized train conditions without elevation, is selected during normal travel and slow train acceleration when the power required for the traction motor is less than the rated power.
- High acceleration (fast acceleration) in pure train conditions is driven by a traction motor when it starts moving from rest to nominal speed. These operating states require a higher amount of power. This additional power requirement can be met from batteries and high capacitors from the supply rectifier substation. Under such conditions, the engine winding can absorb active and reactive power from the two converters connected on its side.
- Regenerative conditions, occur during deceleration or braking of the train. The converter is modulated to return the converted kinetic energy from the traction motor to the connected capacitor. To prevent voltage fluctuations on the common DC link or on the feeder side, no energy is returned to the supply side in this period, by turning off the voltage regulator switch. To ensure that the capacitor voltage when continuous regenerative braking is required, is within a safe operating range, equipment is required to regulate the transfer of excess energy to the battery.
- Stop condition there is no energy conversion needed to be carried out by the traction motor, no converter is needed to switch. However, to prepare the capacitor for the next initial acceleration, the charge state can be activated within this duration, via a voltage regulator switch. In addition, during a normal train journey, load management and voltage stabilization of energy storage components (batteries and capacitors) can be carried out.

CONCLUSION

Given the development of electronic technology—especially IGBT, three-phase induction motors are increasingly being widely used as traction motors in LRT facilities with adjustable working voltage and frequency designs. To make this possible, a supporting component is needed in the form of a VVVF inverter with an output voltage of three-phase alternating current that can be varied and a frequency that can also be varied. The speed of the traction motor is controlled by adjusting the output voltage and frequency of the VVVF inverter where the ratio between the voltage and frequency (V/f) is set constant at 15.7 V/Hz so that the traction motor rotates at maximum torque and at various rotating speeds.

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