Low-cost portable throttle curve manipulator for smooth initial movement of an electric vehicle

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Article Info

Article history:

Received Jun 21, 2022
Revised Dec 30, 2022
Accepted Jan 2, 2023

Keywords:

BLDC motor
Electric vehicle
Initial movement
Throttle curve
Total energy usage
Vibration change

ABSTRACT

This research aims to develop a low-cost portable throttle curve manipulator for a smooth initial movement of an electric vehicle. The hardware is mostly made up of an Arduino and a pulse width modulation (PWM)-to- direct current (DC) converter, which can be easily installed in electric vehicle. The manipulator produces a throttle output curve based on the current throttle input. The suitable throttle output curve is investigated in two stages. First, the four throttle curve types are compared based on motor vibration change and total energy usage during initial movement. They are none, linear, exponential, and polynomial curve types with a delay of 1 s. Then, in the second stage, the delay is varied from 0.5 to 2.5 s. The result shows that the linear throttle curve output with a delay of 1 s produces is appropriate to refine the initial movement of an electric vehicle compared to the polynomial and exponential curve types. The brushless DC electric (BLDC) motor vibration change decreases from 148.75 Hz to 107.45 Hz and total energy usage decreases from 90.64 joules to 87.23 joules. Therefore, the research concludes that the low-cost portable throttle curve manipulator can be developed using a linear throttle output curve with a delay of 1 s.

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1. INTRODUCTION

In recent years, there has been a significant increase in public interest in electric vehicles (EV), particularly for smart city development [1], such as cars [2], motorcycles [3], trains [4], and aircraft [5], because they can be the solution to rapid climate change, which is a major concern for people all over the world [6]-[8]. The change in the direction of vehicle development from combustion engines to electric is caused by the advantage of electric vehicles that they have no tailpipe emissions. An electric vehicle is also more energy efficient compared to a combustion engine vehicle. On the other hand, electric vehicles also have the inherent problem of relatively slow charging of the battery compared to the instant refilling process of gasoline in combustion engine vehicles. A hybrid vehicle aims to overcome this problem by using both a combustion engine and an electric engine in the same vehicle.

This phenomenon also triggers the rapid development of components related to EVs, such as batteries, motors, controllers, and converters [9]. The battery acts as the power source. There are several types of batteries, but lithium-ion is the most commonly used because of its high current and power capability. A motor converts electrical energy to kinetic energy in the form of vehicle movement and sometimes be used as a generator for charging the battery in a hybrid vehicle scenario [10]. The types of motors used in EVs are brushless DC (BLDC) motors, induction motors, and phase motors. Each has its advantages and disadvantages. Therefore, it is imperative to understand the needs of the vehicle to select the proper motor for it. A controller is important to regulate the speed of the motor according to the needs at any point in time. A good controller not only successfully regulates the speed of the motor precisely but is also efficient in terms of energy usage. Lastly, converters (DC/AC and DC/DC) act as a bridge between those components.

Focusing the talk on the motor selection, the brushless DC (BLDC) motor is highly recommended for electric vehicle applications because of the fast response in achieving the maximum rotation per minute (rpm) with efficient energy usage [11]. There has been a lot of research done in the field of BLDC motor control [12]-[15]. The focus of this research is to reach a target rotation per minute (RPM) in the shortest time possible to save the battery [11] and to have smooth movement between the throttle and motor rotation [16]. This method may cause some discomfort to the EV's driver and passengers. This effect can be minimized by slowly pressing the throttle pedal, a technique that is also commonly used in combustion engine vehicles. However, the shock effect in electric vehicles may be greater than in combustion engine vehicles.

The trend in BLDC motor controllers also shifts towards the use of artificial intelligence (AI) [11]. By using AI, some sensors (e.g., encoders and torque sensors) can be eliminated. The result is that the performance and reliability of the BLDC motor driver are improved even when the sensor is eliminated [17]. But still, research about the shock effect in initial conditions is lacking because the focus is usually on the battery, charging method, infrastructure, motor types, and communication between vehicles [18]. The shock can still be felt in the initial movement of the electric car. It is common knowledge that an electric motor responds faster to input compared to a combustion engine. Nowadays, simple electric vehicles (like electric motorcycles) usually suffer from a shock effect in the initial movement because of the quick response of the motor.

It seems like this small phenomenon is missing from public attention because, until this paper was written, no research had been done in this area. This may be caused by the fact that slowing down the response of the system before reaching the target RPM will reduce the efficiency of the system itself. The only reported advancement in this area is the shock effect during changing speed in the moving [19] and the braking state [20] of the electric vehicle, but not about the shock effect felt by the driver when starting to move from a stationary position. Soft-start technology needs to be applied to reduce this effect. Several studies have even found that soft-start technology helps to prevent motor damage [21], avoid over-current while in motion [22], and convert source voltage to operational voltage [24]. Nevertheless, to the extent of the author's knowledge, the soft-start technology for reducing the shock during initial movement is nowhere to be found.

The throttle curve can be adjusted accordingly to avoid the sudden jump or shock effect, which can be done using the software dedicated to the electric vehicle. However, the software is sometimes not accessible by the user unless they have paid a high price for it. Some commercial BLDC motor controllers also do not provide any means of adjusting the throttle curve. Therefore, this research aims to develop a low-cost portable throttle curve manipulator to regulate the rpm (rotation per minute) of the BLDC motor, with a focus on the initial movement of the electric vehicle. The control system differentiates between the initial movement condition and the moving condition based on the current rpm. In the initial movement condition, the rotational speed of the BLDC will be increased slowly until reaching the target rpm to reduce the shock effect. On the other hand, in moving conditions, the target rpm should be reached as quickly as possible to keep the efficiency high.

2. METHOD

2.1. The rest-rig

The research employs a test rig as shown in Figure 1. There is a brushless DC (BLDC) motor and its controller unit, both of which are made by Yalu motor. The operating voltage is 48 V and the power rating of the BLDC motor is 2 kW. The electrical energy for the motor is supplied by a 48 V LiFePO4 battery via the controller. Here, the controller uses throttle output voltage to determine the rotational speed of the motor (in revolutions per minute or rpm). The throttle is a potentiometer that has a range of output voltage of 0.5 V to 4 V. When the throttle is pulled the output voltage increases, and so does the rotational speed of the motor. In contrast, the rotational speed of the motor decreases when the throttle is released.

The throttle curve manipulator is installed between the throttle and the controller, which is built from the microcontroller (Arduino Uno) and a pulse width modulation (PWM)-to- direct current (DC) module. First, the Arduino Uno captures the actual throttle output (T_i) with an idling voltage of 0.86 V and then produces an artificial throttle output in the form of a PWM signal for the converter module. Based on the received PWM signal, the converter module then generates the DC signal of the artificial throttle output for the controller. Since this research aims to find the appropriate throttle output (T_o) as a function of time (t), four throttle curve types are compared in this research. They are none, linear curve, exponential curve, and polynomial curve with a delay (d) of 1 s, as shown in Table 1.

The test rig is also equipped with sensors to monitor the effect of the throttle curve manipulation on the initial movement of an electric vehicle. Two vibration sensors measure the change in vibration of the BLDC motor to represent the sudden change in vehicle movement. The greater the change in vibration, the greater the change in rotational speed of the motor, and thus the greater the change in vehicle movement. Therefore, the least amount of change in vibration of the motor is desired for a smooth initial movement of an electric vehicle. There is also a PZEM sensor, which measures the battery power consumption of the BLDC motor during initial movement. An Arduino Mega collects the sensor's data, which is then logged using PLX-DAQ software with a sampling time of 0.28 s.

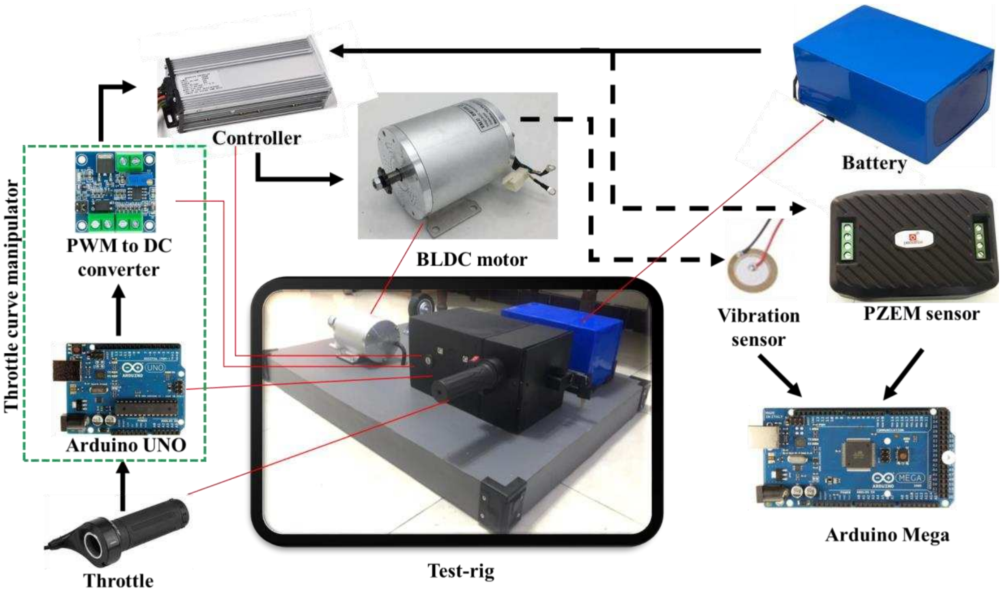

Figure 1. The test rig used in this research. The throttle output voltage was manipulated using Arduino Uno and PWM-to-DC converter module

Table 1. List of throttle curve type

Type	Function
None	$T_o = T_i$
Linear	$T_o = \left(\frac{T_i - 0.86}{d}\right) t + 0.86$
Exponential	$T_o = \left((T_i - 0.86)^{\frac{1}{d}}\right)^t$
Polynomial	$\left(\frac{T_i - 0.86}{d^2}\right) t^2 + 0.86$

2.2. Data gathering

The research conducted data collection in two stages. The collected data in each stage are time stamps, energy usage, BLDC motor vibration change, and throttle output voltage. In the first stage, the best throttle curve type in terms of energy usage and vibration during initial movement is investigated. In each data-collecting session, the throttle is fully pulled instantaneously and held for some time. The throttle is then released until the motor stops rotating before collecting the next data. There are four sessions in the first stage, where each session corresponds to one throttle curve type. In the second stage, the most appropriate delay is investigated. The procedure is the same, but using only the best throttle output type from the first stage with varying delay from 0.5 to 2.5 s with an increment of 0.5 s. Therefore, there are five sessions of data collection in the second stage.

2.3. Information processing

In each session, fifteen energy usage and change-in-vibration data samples were collected, each of which is recorded during the rise of throttle output voltage from the lowest point to the highest point. Five samples with unusual total energy usage (largely deviating from the average of the sample population) were then excluded, leaving only ten samples. Then, the collected energy usage and change-in-vibration data were used to calculate their average value and standard deviation. The average elapsed time was also calculated. For the throttle output voltage, the average value is only calculated after the samples are interpolated to have identical data points.

3. RESULTS AND DISCUSSION

3.1. Throttle curve generation

The throttle curve manipulator has successfully generated the desired throttle curves, as shown in Figure 2. The blue triangle line is the non-manipulated throttle curve; the red circle line is the linear throttle curve; the orange diamond line is the exponential throttle curve; the purple star line is the polynomial throttle curve. The manipulated throttle curves achieve the highest output voltage after a small delay. Figure 2 shows that the time needed for the linear, exponential, and polynomial curves to reach the highest output voltage is approximately 1.3 s while the non-manipulated curve reaches the highest output voltage after approximately 0.6 s. The added delay of the manipulated throttle curves thus is approximately 0.7 s.

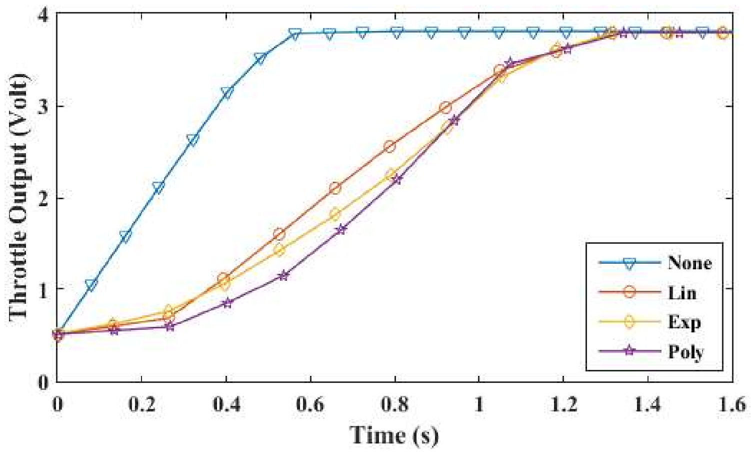

Figure 2. The throttle output voltage generated by the throttle curve manipulator during initial movement

3.2. Effect of throttle curve type

The comparison of different throttle curve types in terms of vibration change and energy usage of the BLDC motor is presented in Figure 3. Figure 3(a) shows the vibration change and Figure 3(b) shows the energy usage. The highest change in vibration belongs to the non-curve type. The change in vibration decreases when the throttle curves are manipulated. In particular, the exponential curve type ranks first as the throttle curve that has the lowest motor vibration change with a value of 95.9 Hz. The linear curve type and polynomial curve type were placed second and third, with vibration changes of 100.8 Hz and 127.75 Hz, respectively.

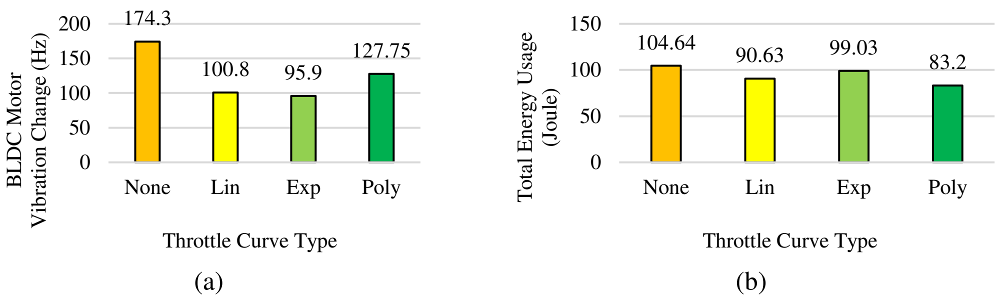

Figure 3. The effect of throttle curve type to the (a) change in vibration of the BLDC motor and (b) total energy usage during initial movement

The result also shows that the total energy usage decreases because of the throttle curve manipulation. However, there was a slightly different pattern. The polynomial curve type now produced the lowest energy usage of 83.2 joules, while the exponential curve type produced the highest energy usage of 99.03 joules. The linear curve type stays in between the polynomial and exponential curve types with a total energy usage of 90.63 joules. As a result, the linear type provides balanced advantages where both the energy usage and vibration change are not too high or too low. Then, the research concludes that the linear curve type is the best throttle curve compared to the exponential and polynomial curves.

3.3. The impact of delay

The initial movement of an electric vehicle has been simulated using a linear throttle curve type with several delays, such as 0.5, 1, 1.5, 2, and 2.5 s. Figure 4 shows the effect of the delay on the change in vibration of the BLDC motor and total energy usage during the initial movement of an electric vehicle. The longer the delay, the less the change in vibration of the BLDC motor. The non-manipulated curve (labeled as None in Figure 4(a)) type has a slightly different change in vibration than the lin0.5 curve type, which is 148.75 Hz compared to 154 Hz. When the delay increases to 1 s, the change in vibration decrease significantly from 154 Hz to 107.45 Hz. After that, the change in vibration decreases a little to 72.45 Hz when the delay is 1.5 s. The decrease change continues to be smaller as a change of 67.2 Hz was observed when the delay is 2 s and 50.05 Hz when the delay is 2.5 s.

Meanwhile, the total energy usage exhibits different behavior when the throttle curve is subjected to different delays, as shown in Figure 4(b). The non-manipulated throttle curve type uses 90.64 joules, while the lin0.5 and lin1 curve types use 74.61 and 87.23 joules, respectively. Throttle curve manipulation can decrease the total energy usage during the initial movement. However, if the delay is made longer than it should be, the opposite effect occurs. When the throttle curve is delayed, more energy is consumed during the initial movement of the electric vehicle. This behavior can be observed by the total energy usage of 219.03 joules when the delay of the linear throttle curve is 2.5 s.

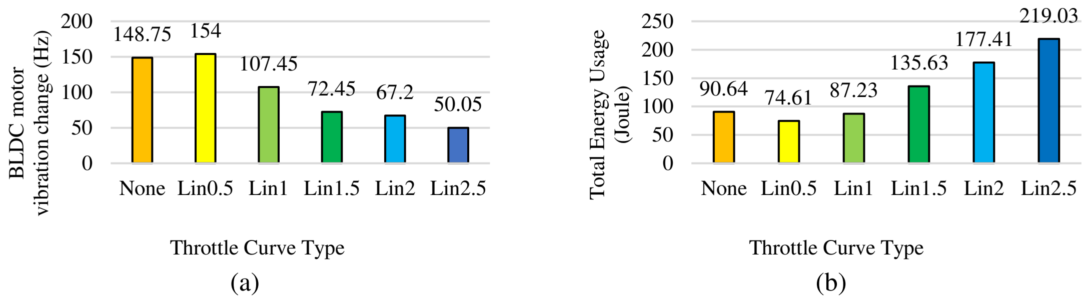

Figure 4. The effect of different delays on linear throttle curve type to the (a) the effect of different delays on linear throttle curve type to change in vibration of BLDC motor and (b) total energy usage during initial movement

3.4. Discussion

Encouraging people to move from an internal combustion engine (ICE) vehicle to an EV is a tedious task. One way is to ensure comfort during the riding of an electric vehicle. Previous studies have paid attention to this comfort aspect. Brake-by-wire system is reported in [25], where the hydraulic brake is changed to an electric braking system. Although the brake-by-wire is more efficient compared to the hydraulic brake, the brake does provide a feedback force when the pedal is pressed, unlike the hydraulic brake system. The feedback force is important because the driver feels uncomfortable when pressing a button without it. Therefore, a feedback force is displayed to increase the user's comfort in using the brake-by-wire system. Other research reports a time-to-collision calculation to stop an electric vehicle by releasing the throttle without any applied braking force [26]. As a result, the stopping action becomes smoother and more comfortable for the user on board.

Meanwhile, this research focuses on the comfort aspect of the initial movement rather than the stopping action. This research has evaluated several throttle curves for developing a low-cost portable throttle curve manipulator. High torque output means high motor rpm and so is the movement speed. If the throttle output increases by a wide margin instantly, then the motor rpm also changes drastically. The electric vehicle will experience a high impulse, which results in a sudden jump during initial movement. Slowing down the motor response to avoid the sudden jump is not suggested by a previous study [27]. Instead, the motor should respond quickly and accurately to avoid stability issues during operation. Indeed, a motor controller should be designed to drive the motor most effectively and efficiently. And if the motor controller is designed to support the BLDC motor to respond quickly and accurately, then modifying the motor controller to solve the problem of sudden shock during the initial movement of the vehicle is out of the question. Gradually increasing the throttle output is the key to a smooth initial movement of an electric vehicle. Therefore, the developed throttle curve manipulator should have a small and constant gradient.

The result has shown that the appropriate throttle curve type is the linear curve type. The reason is that the linear curve type performance stays in between the polynomial and exponential curve types with a change of 100.8 Hz in the vibration of the BLDC and total energy usage of 90.63 Joule, as shown in Figure 3. The linear throttle curve type has an edge compared to the other throttle curve types because it has a constant gradient. Although a previous study by [28] shows that the throttle curve should be a polynomial, this study suggests that the polynomial is not the most appropriate choice. The gradient of the polynomial and exponential curves is lower than the linear curve at the beginning. But, after some time, the gradient surpasses the linear curve gradient as shown in Figure 2. The non-linear curve might produce an efficient output due to the gradient of the curve changing over time. However, the change in gradient also contributes to the sudden change in vibration, which is avoided in this study.

Starting with the small gradient has its advantages. A motor uses more energy to get started, usually double the rated power specification [29]. But, if the motor is already rotating, then it only needs a little energy to increase the motor rpm. This phenomenon is observed in the test result of the polynomial throttle curve type, where the total energy usage of 83.2 joules is the lowest compared to the other throttle curve types. However, the gradient increased, which resulted in the highest change in vibration of 127.75 Hz.

By calculation, the exponential curve starts from 1 instead of 0 at a time equal to zero. Therefore, it is natural that the throttle output voltage is higher at the beginning compared to the linear and polynomial curves. Because of that, the total energy usage is the highest, which is 99.03 joules. After that, the gradient increases, but not as steep as the polynomial curve. As a result, the change in vibration is not as high as in the polynomial curve. Instead, the exponential curve scored 95.9 Hz in terms of change of vibration, which come close to the linear curve result which is 100.8 Hz.

The delay plays an important role in balancing the trade-off between the change in vibration of the motor and the total energy usage. A short delay resulted in a higher curve gradient, which consequently increased the motor vibration, as shown in Figure 4. Making the delay longer seems the better choice. However, the longer delay resulted in higher total energy usage during initial movement. The result is understandable because this situation is like starting the vehicle movement by applying the same throttle curve type but slowly. A moderate delay of 1 s is the appropriate delay, as has been shown by the results in this research. However, future studies should also investigate the effect of delay on the other throttle curves. For instance, the polynomial curve is suggested by a previous study [28], but this research suggests utilizing the linear throttle curve. Different delays on the polynomial curve might give different results, thus it is worth to be investigated in future studies.

The development of a low-cost portable throttle curve manipulator that decreases the change in vibration of BLDC motor without excessive energy usage is possible. The manipulator can achieve the desired result by employing the linear throttle curve type with a delay of 1 s. The hardware consists of an Arduino and a PWM to DC converter only. The cost is less than $25, which makes the proposed manipulator cheap enough to ensure a smooth initial movement of an electric vehicle. The proposed manipulator can be put in between the controller and the throttle, and the electric vehicle's battery can be used to power it. Tracking the throttle output accurately is not presented in this study despite the importance of ensuring the desired throttle output, as shown in previous work by [30], [31]. Future studies should implement a throttle output tracking algorithm by adding some code inside the Arduino. Additional circuits might not be necessary so the compactness can be retained. However, the possibility of increased computational time due to the increased complexity of the algorithm should also be considered.

Some commercial BLDC motor controllers already include a built-in throttle curve setting, which can be adjusted manually for smooth movement. The throttle curve setting affects the BLDC motor's response to the throttle output [23], [32]. By setting the motor response as fast as possible, the energy usage can be optimized [14], but the fast response will result in unwanted sudden initial movement. On the contrary, a slow response on a BLDC motor will result in inefficient energy usage. This research proposed a different approach, which is altering the throttle output received by the BLDC motor controller without changing the BLDC motor response. As a result, the BLDC motor response can be set to be as fast as possible, but now the BLDC motor also has a smooth initial movement. However, the concept has not been proven in a real-world implementation. Therefore, future studies should investigate the effect of throttle curve manipulation on the real initial movement of an electric vehicle. The effect of different terrain on the performance of BLDC motors is also an interesting parameter to be investigated, as has been demonstrated by a previous study [10].

4. CONCLUSION

This research has developed a low-cost portable throttle curve manipulator. The manipulator hardware consists of an Arduino microcontroller and a PWM-to-DC converter module, which can be installed easily between the throttle and the motor controller. Software-wise, the manipulator uses the linear throttle curve type with a delay of 1 s. An experiment has been conducted to see the effect of the linear throttle curve type on BLDC motor vibration change and total energy usage during initial movement. The result shows that the change in vibration of the BLDC motor decreases from 148.75 Hz to 107.45 Hz and the energy usage decreases from 90.64 joules to 87.23 joules when the linear curve type is used instead of the non-manipulated curve type. Therefore, the proposed throttle curve manipulator has the potential to be implemented because it can decrease the BLDC motor vibration change without excessive energy usage. The sudden initial movement can be avoided without reducing the response of the BLDC motor to the throttle output, which is the main feature of the proposed low-cost portable throttle curve manipulator. Several future studies related to this research have been addressed as follows. First, the future study should investigate the effect of delay on the other throttle curve types (e.g., polynomial and exponential). Second, a throttle output tracking algorithm is important to be developed so the desired throttle output can be ensured. Lastly, future studies should investigate the effect of throttle curve manipulation in a real-world scenario. The effect of different terrain on the performance of BLDC motors during the initial movement is also an interesting parameter to be investigated further.

ACKNOWLEDGEMENTS

The authors would like to thank Institut Teknologi Telkom Surabaya for funding this research under research contract 1012/PNLT1/LPPM/III/2021.

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