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RESEARCH ARTICLE

Effect of Inverter Frequency on Electric Motor-Driven Air Conditioning Systems Repurposed from Combustion Engine Cars for Electric Vehicle Applications

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Abstract

With the growing need for sustainability and the positive impact of electric vehicles (EVs) for a greener environment, and their sustainability in the automotive system, this research explores the adaptation of air conditioning (AC) systems from conventional vehicles to be reused in EV conversions, by changing the system drive from engine rotation to an electric motor whose frequency can be adjusted by an inverter. The study observes the system's performance based on variations in motor frequency and AC blower speed to determine optimal operational parameters. The data obtained indicate that these variations affect cooling performance and energy consumption, to obtain efficient results in cooling the cabin. The results highlight optimal settings for minimizing energy consumption while achieving effective cooling, providing valuable insights for sustainable EV conversions.

Keywords: Electric Vehicle Conversion, Automotive Air Conditioning System

1. Introduction

Pollution is a significant contributor to global warming, leading to an overwhelming environmental challenge, such as earth's temperature rising, the polar ice caps are melting, causing sea levels to rise and threatening coastal ecosystems and human settlements [1]. Additionally, pollution contributes to the depletion of the ozone layer, amplifying harmful ultraviolet radiation exposure, and triggering various extreme climate phenomena, such as hurricanes, droughts, and irregular weather patterns. Addressing pollution is, therefore, a critical step in mitigating these global challenges and preserving the planet for future generations.

One of the strategies to reduce pollution is transitioning to electric vehicles (EVs). Unlike internal combustion engine vehicles, EVs produce zero tailpipe emissions, significantly lowering air pollution and greenhouse gas emissions. Parallel to the rapid growth and environmental benefits of EVs, the energy sources used often come from renewable power plants, such as solar, wind, or hydropower, which can maximize their eco-friendly potential and ensure a sustainable transition away from fossil fuel dependence [2].

Government also issuing policies aimed at phasing out internal combustion engines, as declared in many countries, such as Singapore at 2030 [3], certain states in USA at 2035 [4], EU at 2035 [5], UK at 2040 [6], and Vietnam at 2040 [7]. While nations like Indonesia, Malaysia, and New Zealand have announced similar plans, formal government directives are yet to be issued.

Beyond adopting EVs, converting existing internal combustion engine vehicles into electric ones presents a more sustainable alternative to manufacturing new cars. Producing new vehicles consumes vast amounts of energy and resources and leads to additional waste from the disposal of old cars [8], [9], [10]. By repurposing functional parts such as the chassis, interior fittings, and systems like audio, lighting, and air conditioning (AC), the proposed method minimizes waste and reduces the energy required to build an electric vehicle. This approach not only lowers the environmental footprint of car conversions but also makes the transition to EVs more affordable and accessible for consumers. In doing so, it provides a practical and eco-friendly alternative to mass production of new vehicles, contributing to the broader goal of sustainable development and pollution reduction.

This paper proposes a sustainable approach to electric vehicle conversion by repurposing existing AC systems. By modifying the original AC system to operate with an electric motor instead of a combustion engine, the conversion process becomes more efficient and resourceconscious, retaining essential functionalities without significant additional resources. To evaluate this approach, an experiment was conducted on an AC system from a combustion engine car and operated independently of a vehicle. This setup enabled precise control and analysis of the system's performance under various inverter frequency settings, providing insights into its energy requirements and potential for sustainable reuse in electric vehicle applications.

2. Workflow of Car AC system

To provide cooling and dehumidification, car AC comprise of different components such as compressor, condenser, condenser fan, drier, expansion valve, and evaporator, using refrigerant and oil circulating inside.

The workflow of Car AC system seen on Figure 1 starts when the AC turned on, thermostat control unit sends a signal to engage the compressor clutch, driven by engine pulley connected by a belt to compress the refrigerant inside, making it high pressure, high temperature gas. This hot compressed gas flows into condenser to be cooled through condenser coils, shaped with many fins and tube to release heat to

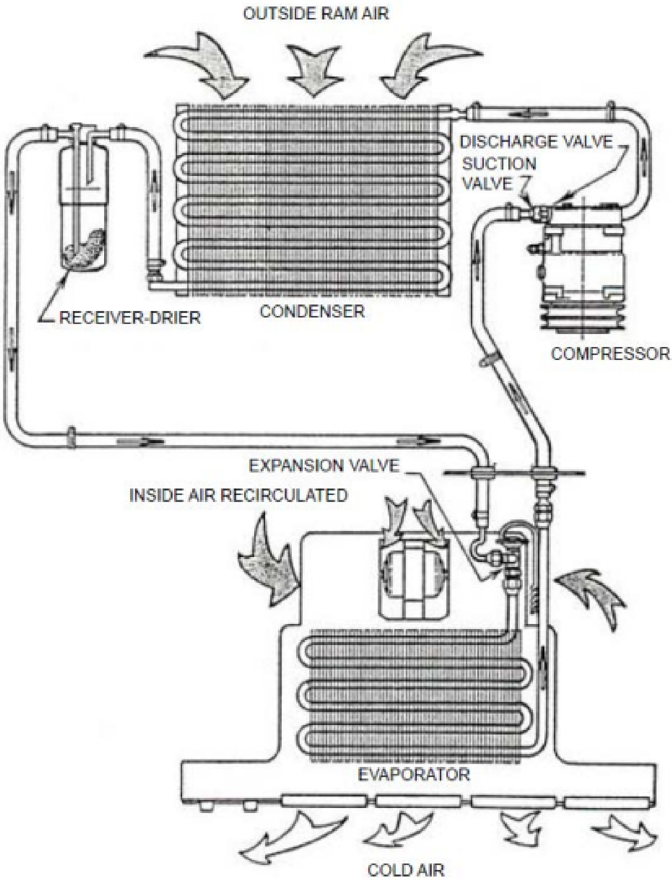

Figure 1. Workflow of Car AC System [11]

the surrounding air. Condenser fan fitted to it to make the heat exchange even more efficient, making the cooling process even better.

After it loses heat, the refrigerant changing into high pressure, low temperature liquid. The refrigerant now flows into receiver/drier, to separate any remaining gas from the liquid form, to ensure that only in liquid form flows into the expansion valve. In expansion valve, the high pressure, low temperature liquid encounters a dropping pressure, leading a phase change of refrigerant from liquid to vapour, making it temperature even lower. This mixture of low pressure, low temperature liquid and vapour enters the evaporator.

Evaporator works by absorbing heat from the air, by having fins and coils to improve heat transfer, where the refrigerant flow. When the heat air absorbed from interior of the car pass through evaporator, it becomes cold air, blowing it back into cabin with the cabin blower motor through AC vents. In addition to cooling the air, this part also plays a role for dehumidifying car interior.

When hot air passes over cold evaporator coils, moistures formed on the evaporator coils, forming water droplets. Collected water droplets has its own hose pipe to be drained out of the car, reducing the humidity level inside the cabin. After passing through evaporator, the refrigerant, now in low temperature, low temperature gas flowing into compressor, compress it again back to be high pressure, high temperature gas, and repeating the cycle, until it reached the temperature set by thermostat control unit. After reaching that temperature, another signal sent to disengage the compressor clutch.

The refrigerant used in car AC system globally are using R134a, after completely phasing out R12 for its lower flammability and safety risk, as well lower risk to global warming. If CO^2 having 1 Global Warming Potential (GWP), releasing the same amount of R12 to atmosphere will resulting in 8500 GWP, and releasing R134a will have 1300GWP [11]. The refrigerant in AC system mixed with certain amount of refrigeration oil to provide lubrication, easing the workflow cycle, as shown in Figure 2

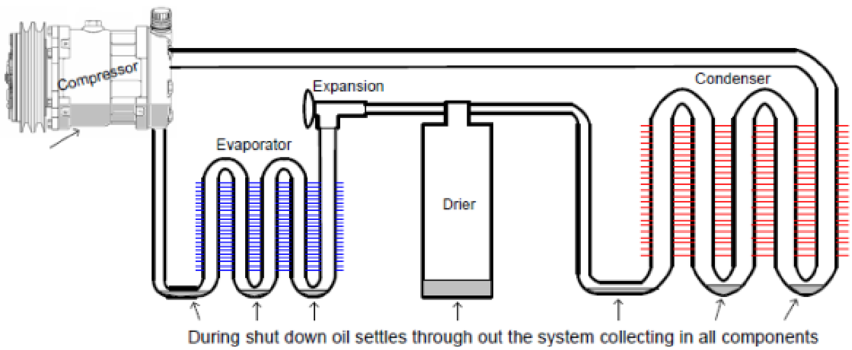

Figure 2. Oil and Refrigerant Position in Off Condition [12]

Dismantling car AC first step is by discharging refrigerant inside the system, using proper discharge system, not releasing it into atmosphere. Not only it's damaging to environment, based on its GWP, which can tear hole in earth ozone layer, it is also ruled out by government [13], [14], [15], [16]. Further energy saving can be achieved by refilling it back using discharged refrigerant to the same system after assembling it back.

3. Experimental Setup for Car AC System Using Electric Motor

As previously mentioned, AC system starts from compressor, when the compressor clutch engages driven by engine pulley connected by a belt to compress the refrigerant. In order to utilizing the AC system into electric car with minimum replacement with new parts, the proposed works will be driving the compressor using electric motors pulley, with varied frequency using inverter to achieve data of power and cooling rate.

When installing it on converted car, it needs to be using Brushless Direct Current (BLDC) motor with DC inverter, but this experiment is yet to be fitted to the unavailable said car, so the alternative motor used are what's available, three phase motor with AC inverter. 12V car battery will be used to move blower fan, condenser fan, and compressor clutch.

The whole car AC system are assembled on compact sized rack, with dimension of 122x47x72 cm since it was need to be moved a lot, from building, assembly, test run, and taking the data can't be done in one place. Dividing it to 2 level, as shown on Figure 3, making the bottom part fit electric motor, inverter, car battery, and the exterior cabin AC component such as compressor, condenser, condenser fan, and drier. Top part act as interior cabin having AC unit, already consist of expansion valve, evaporator, blower fan, thermostat control, and AC vent, enclosed on each side to remove interference with outer air flow and lighting, shown on Figure 4 with top enclosure side removed.

The component mentioned are standard three phase motor with maximum RPM of 1400 and maximum frequency of 50Hz, Sanden 507 compressor, commonly used for sedan, hatchback, and MPV type cars, inverter ABB ACS550, car battery GS 36B20L with 35Ah maximum load, and pro-tech AC unit. Refrigerant charged into the system, and must only filled through low pressure side, with readings of 25 psi on low pressure side, and 155 psi on high pressure side. In this model, the valve was filled on compressor head, having preloaded with refrigerant oil.

Figure 3. AC System Setup

3.1 Acquiring Data from AC System

To acquire data needed, 2 Clamp-on power logger model Hioki PW3360-21 are used to measure power usage, one from main electric panel to inverter, and another one on inverter to electric motor. Digital thermometer model Lutron TM-946 are used to

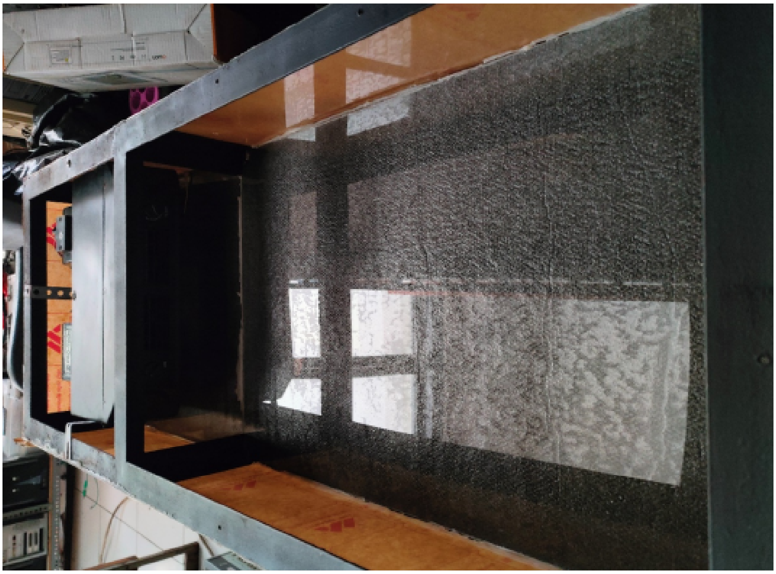

Figure 4. Top Part Where the AC Unit is, Acting as a Cabin

monitor the temperature drop rate, with 2 sensors fitted inside, far in front of AC unit on left and right side. The data presented recorded in every second interval, monitored from highest to lowest temperature, from compressor clutch engage until disengage, running with 3 different blower fan speed available on AC unit, and frequency from electric motor. The lowest start from when compressor can work properly is 25, thus the data acquired are 25, 30, 35, 40, 45, and to 50 Hz.

This will show how long the AC can lower temperature inside the cabin until compressor disengage, how much the power needed, and on which frequency is the best settings according to the data. This data acquisition steps can be seen on flowchart Figure 5

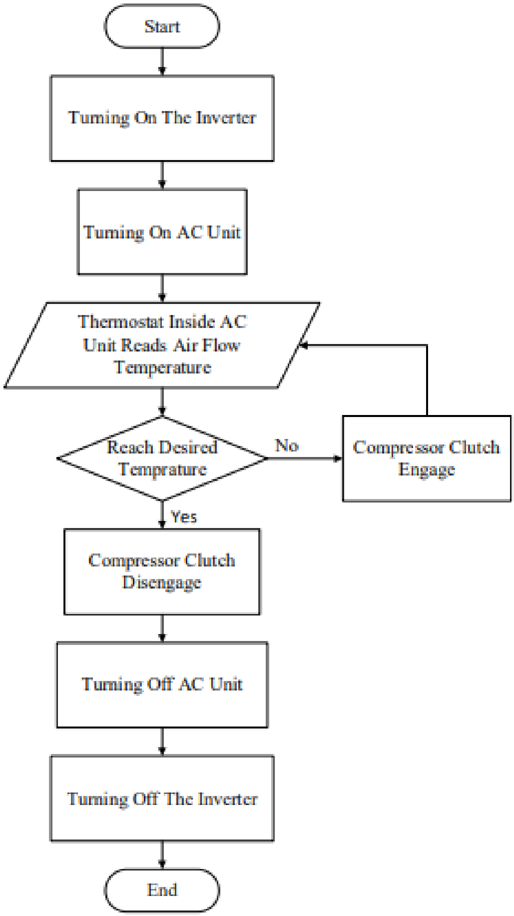

Figure 5. Operational Flowchart of AC System

3.1.1 Data Analytics of AC System with Blower Fan Speed 1

Graph shown on Figure 6 to Figure 12 are the data acquired on different inverter frequency set with blower fan speed set at its lowest settings, 1. The blue line represent power from main to inverter, and the red line represent power from inverter to motor recorder on power logger. Grey line are temperature recorded on the left side inside the cabin and yellow on the right side, recorded on thermometer. The first hike on the graph are when the inverter turned on, then turning on the AC unit. Each second the time pass, the lower the temperature becomes, since AC unit works by recirculating cold air inside the cabin, making it even cooler. The drop goes on until thermostat inside AC unit telling compressor to disengage, but the motor still spinning until inverter turned off, hence graphs below show the power didn't drop immediately to zero.

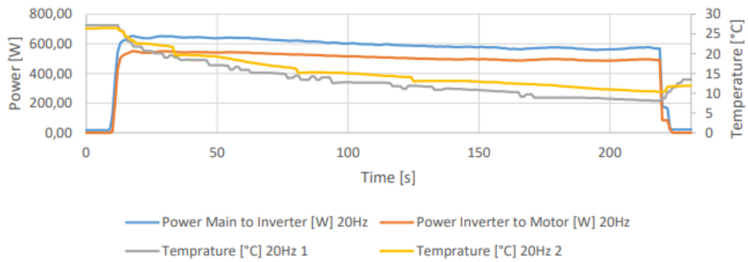

Figure 6. Power and Temperature Chart on Blower Speed 1 and 20Hz Frequency

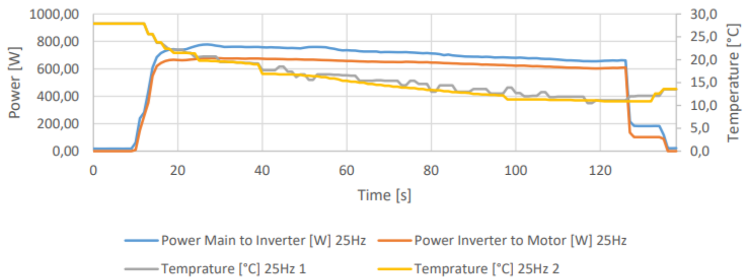

Figure 7. Power and Temperature Chart on Blower Speed 1 and 25Hz Frequency

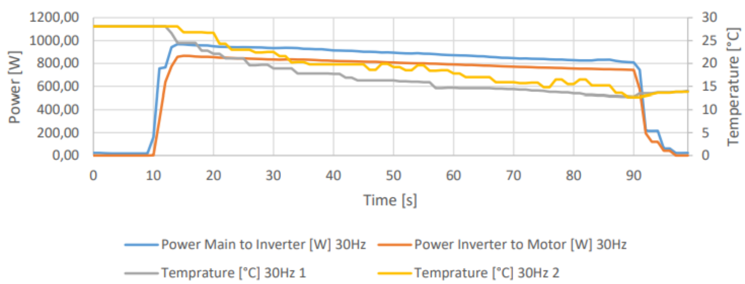

Figure 8. Power and Temperature Chart on Blower Speed 1 and 30Hz Frequency

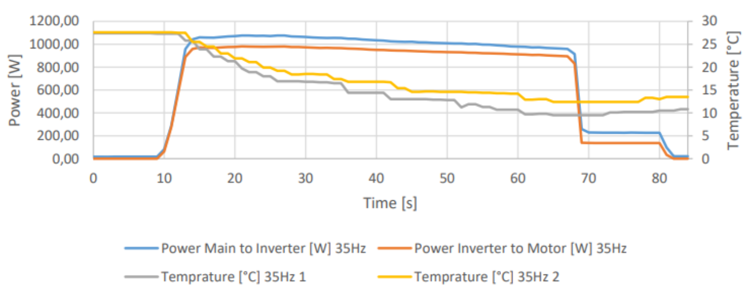

Figure 9. Power and Temperature Chart on Blower Speed 1 and 35Hz Frequency

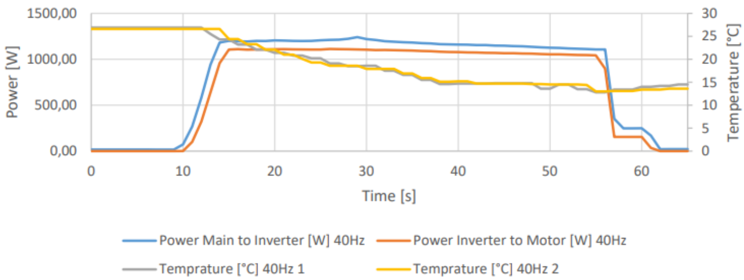

Figure 10. Power and Temperature Chart on Blower Speed 1 and 20Hz Frequency

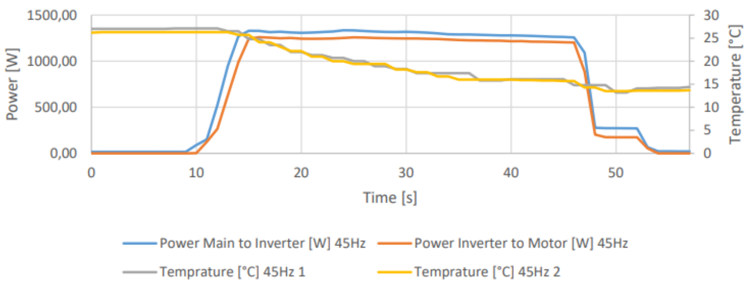

Figure 11. Power and Temperature Chart on Blower Speed 1 and 45Hz Frequency

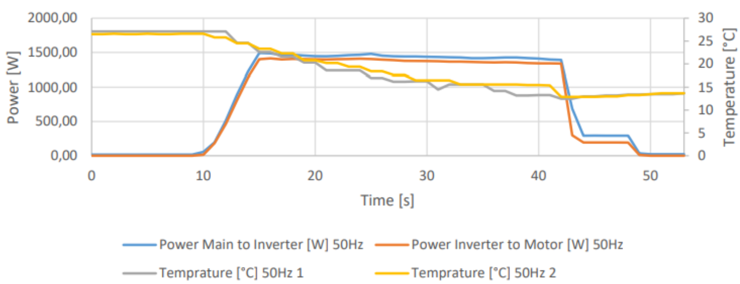

Figure 12. Power and Temperature Chart on Blower Speed 1 and 50Hz Frequency

Graphs displayed on Figure 6 to Figure 12 prove the higher motor frequency is, the faster cabin got cooler, and the faster compressor got disengage, but the power needed to drive it also needs to be higher, with maximum 1500 W. Figure 13 proving it by comparing energy usage from acquired data with one watt of power for one hour by using Equation 1, and the best setting is by using 50Hz with 12Wh energy usage.

$$Wh = \Sigma P/3600 \tag{1}$$

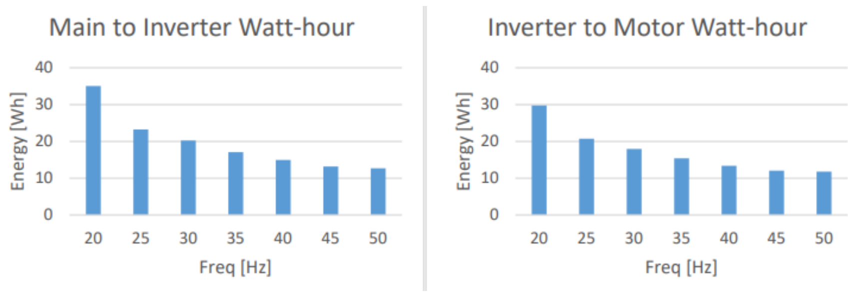

Figure 13. Energy Comparison on Each Frequency

Figure 13 show power difference from main to inverter and from inverter to motor used to change the power usage and frequency. Equation 2 are used to calculate inverter efficiency on each run, shown on Figure 14, averaging 86% efficiency.

$$Efficiency = \Sigma \left(\frac{P_{(inverter-motor)}}{P_{(main-inverter)}} \right) \tag{2}$$

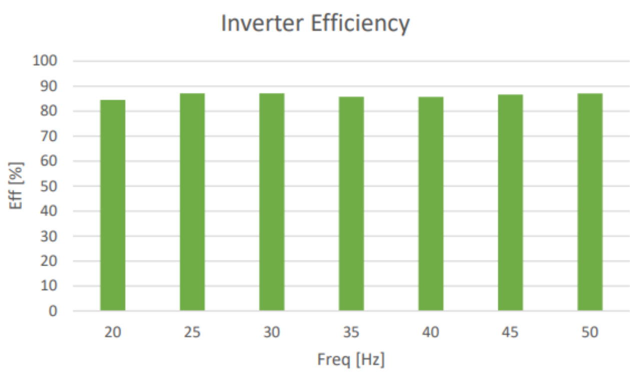

Figure 14. Inverter Efficiency Comparison on Different Frequency

British Thermal Unit (BTU) is a standard unit of measurement used to determine the cooling capacity of an air conditioner. BTU rating refers to their capacity to remove heat from the air. Calculating BTU of AC in a designated room can be shown by using Equation 3 [17], with air density ρ =1.1934kg/ m^3, and air capacity c=1004 J/kg°C [18]. V are volume of the cabin and ΔT are temperature difference. Q value result in Joule to BTU can be achieved by dividing it with 1055, shown on Figure 15 on each frequency, averaging 1,96 BTU.

$$Q = \rho \times V \times c \times \Delta T \tag{3}$$

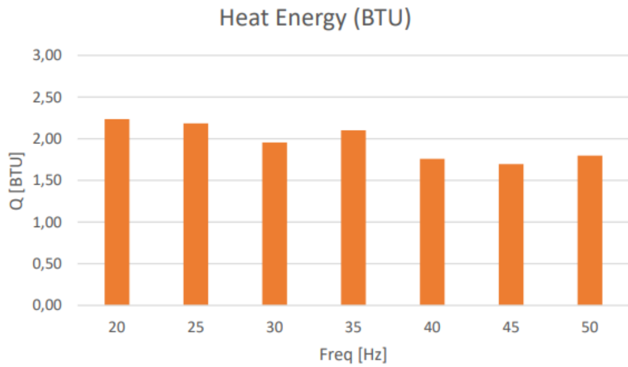

Figure 15. BTU Comparison on Each Frequency

3.1.2 Data Analytics of AC System with Blower Fan Speed 2

The same step done as previously, the only difference is the blower fan speed set on the middle settings, 2, shown on Figure 16 to Figure 22.

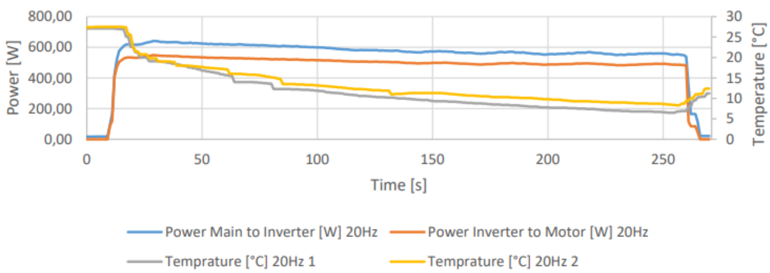

Figure 16. Power and Temperature Chart on Blower Speed 2 and 20Hz Frequency

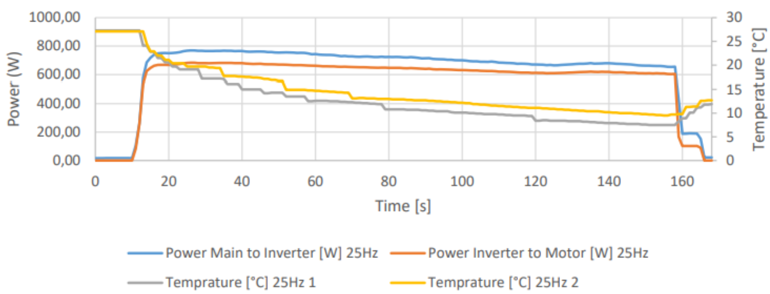

Figure 17. Power and Temperature Chart on Blower Speed 2 and 25Hz Frequency

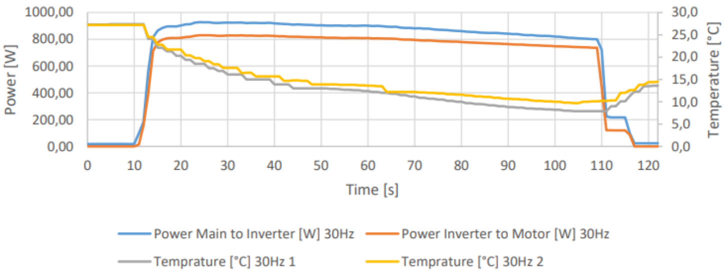

Figure 18. Power and Temperature Chart on Blower Speed 2 and 30Hz Frequency

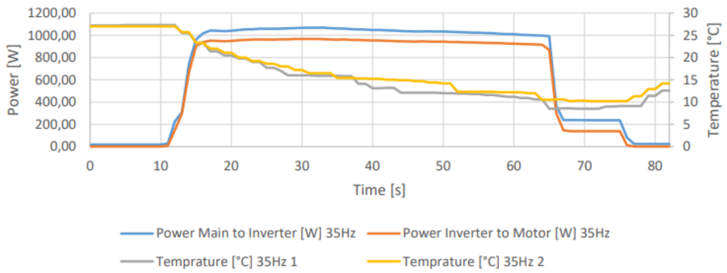

Figure 19. Power and Temperature Chart on Blower Speed 2 and 35Hz Frequency

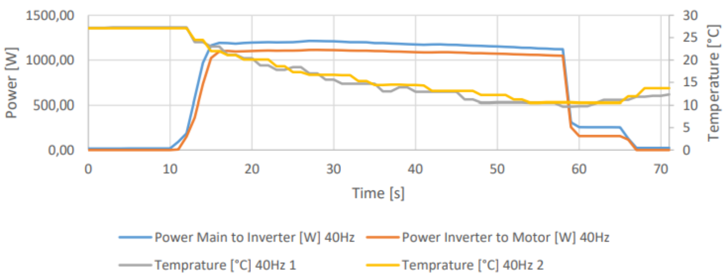

Figure 20. Power and Temperature Chart on Blower Speed 2 and 40Hz Frequency

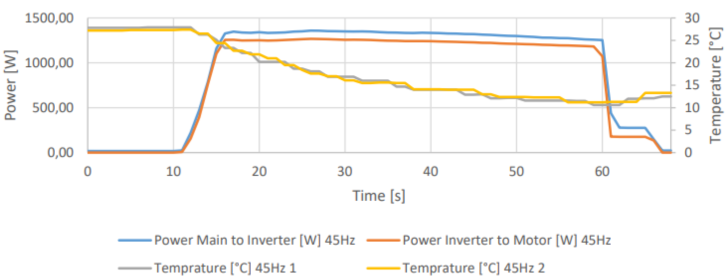

Figure 21. Power and Temperature Chart on Blower Speed 2 and 45Hz Frequency

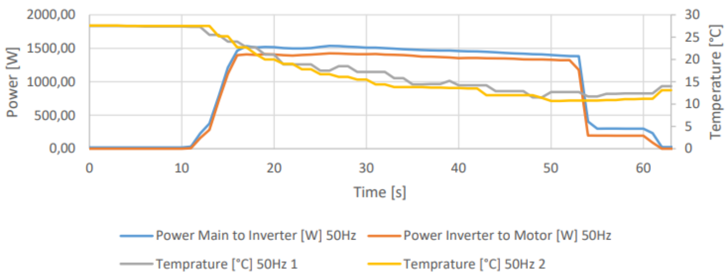

Figure 22. Power and Temperature Chart on Blower Speed 2 and 50Hz Frequency

Graphs displayed on Figure 16 to Figure 22 still prove the higher motor frequency is, the faster cabin got cooler, and the faster compressor got disengage, but the bigger power needed, with maximum read of 1500 W. But in case of energy, 40Hz was the best setting as shown on Figure 23 with 14 Wh. This will be covered on the next blower fan speed setting data analysing

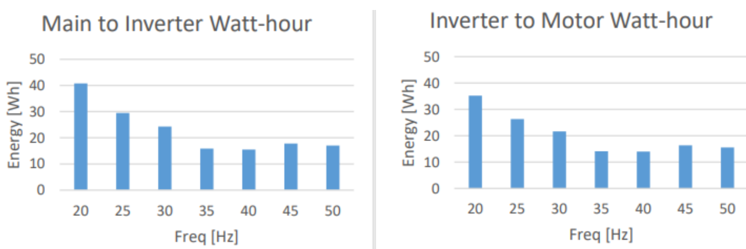

Figure 23. Energy Comparison on Each Frequency

Using the same step as before, inverter efficiency on blower fan speed 2 shown on Figure 24, using the same calculation using Equation 2, averaging 87% of efficiency.

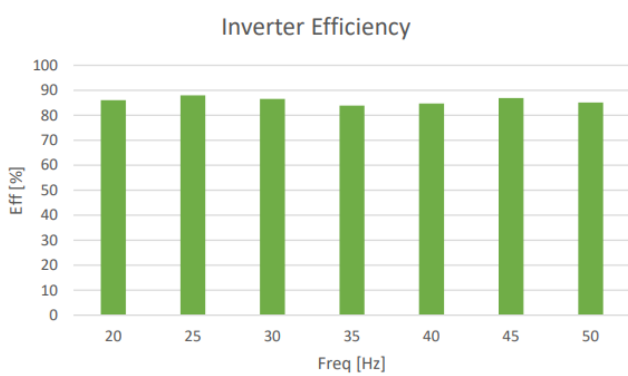

Figure 24. Inverter Efficiency Comparison on Different Frequency

BTU rating on this run is shown on Figure 25, calculated using Equation 3 with average BTU of 2,27.

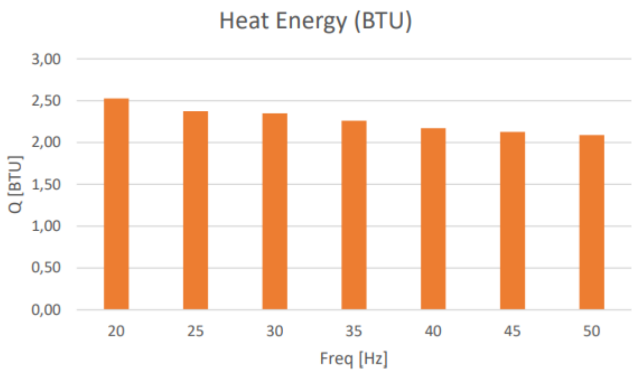

Figure 25. BTU Comparison on Each Frequency

3.1.3 Data Analytics of AC System with Blower Fan Speed 3

The final data acquired are on the highest blower fan setting, blower fan speed 3, shown on Figure 26 to Figure 32.

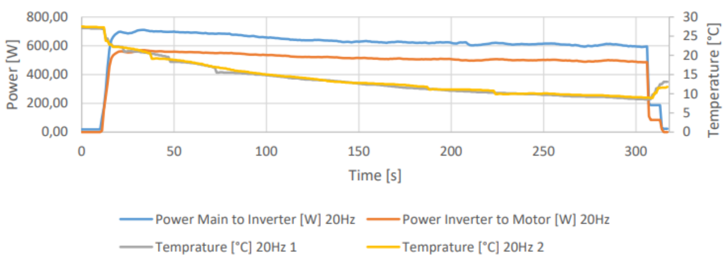

Figure 26. Power and Temperature Chart on Blower Speed 3 and 20Hz Frequency

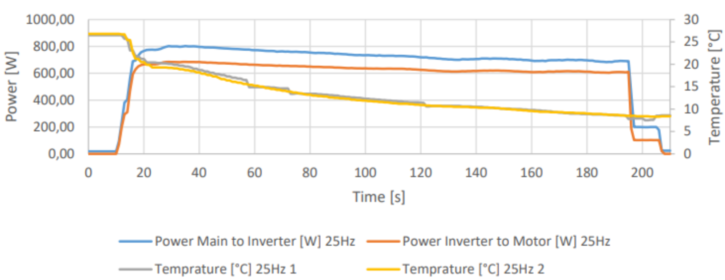

Figure 27. Power and Temperature Chart on Blower Speed 3 and 25Hz Frequency

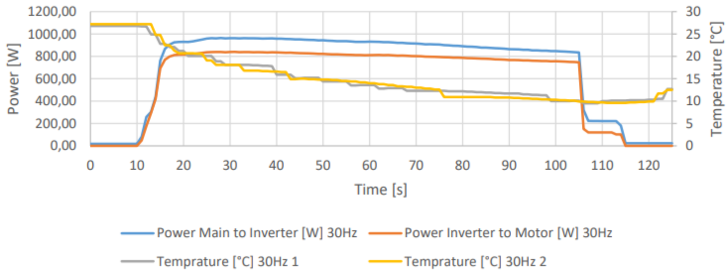

Figure 28. Power and Temperature Chart on Blower Speed 3 and 30Hz Frequency

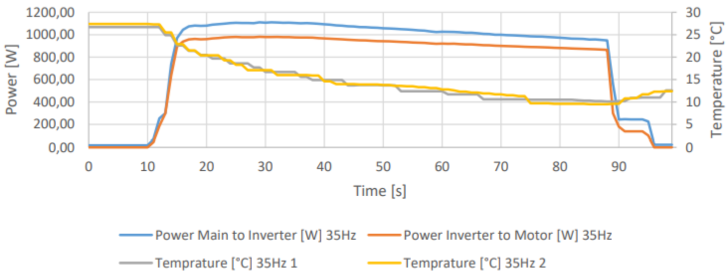

Figure 29. Power and Temperature Chart on Blower Speed 3 and 35Hz Frequency

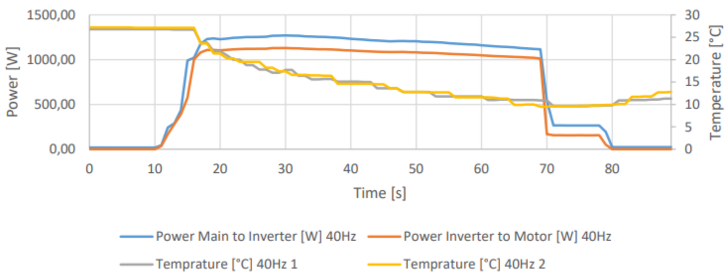

Figure 30. Power and Temperature Chart on Blower Speed 3 and 40Hz Frequency

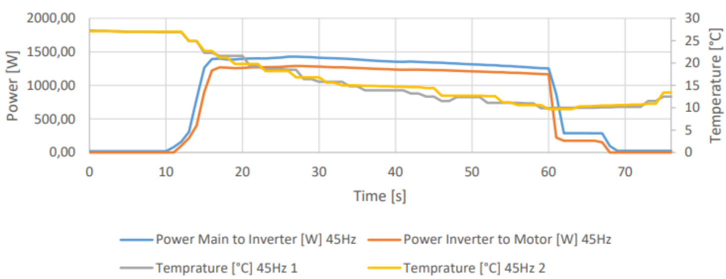

Figure 31. Power and Temperature Chart on Blower Speed 3 and 45Hz Frequency

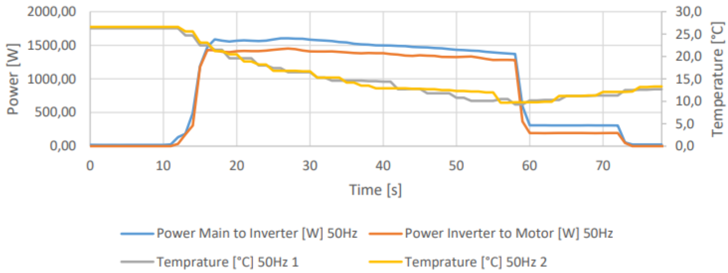

Figure 32. Power and Temperature Chart on Blower Speed 3 and 50Hz Frequency

Graphs on Figure 26 to Figure 32 also show the higher the frequency given, the faster the temperature drop, but the time it takes are longer although the blower speed fan get higher. In case of power monitored on main to inverter able to reach 1600W. Shown on Figure 33, the best setting set at 45Hz with energy usage at 16Wh. This inconsistent result also shown on Figure 23 for fan speed 2 depends on where the blower fan got power from, the car battery. Without source to charge the battery back, the power available to keep moving the fan keeps dropping every run, making the supposed highest setting not having the best energy usage result

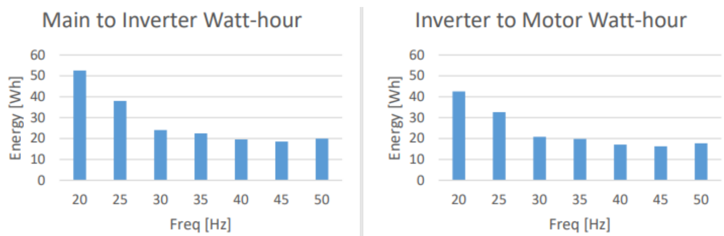

Figure 33. Energy Comparison on Each Frequency

Inverter efficiency on each frequency on this run are shown on Figure 34, averaging 84% efficiency.

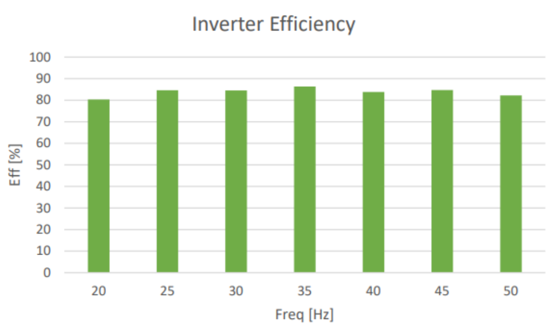

Figure 34. Inverter Efficiency Comparison on Different Frequency

BTU rating on this run shown on Figure 35, averaging 2,25 BTU

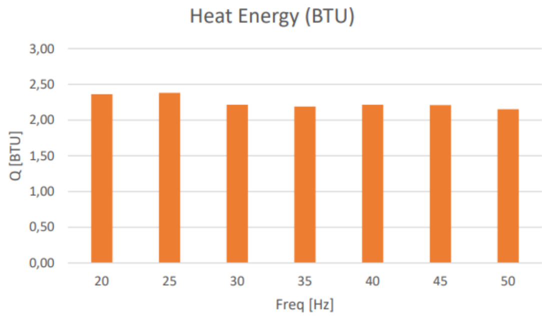

Figure 35. BTU Comparison on Each Frequency

3.2 Acquiring Data from AC System with Additional Alternator

After collecting all the data needed, the car battery voltage dropped, since there is no power source to fill car battery back, and the power will get depleted until it run flat. Instead of getting a new AC to DC converter, or DC to DC converter when fitting it into the car, another parts that can be utilized is alternator. By connecting it with belt to drive it shown on Figure 3, it can charge back car battery, maintaining its voltage stability. Car alternator works with its lamp indicator, when illuminated it indicates the alternator isn't charging. The current used to illuminate the lamp flows though the field windings in the alternator which is what enables it to produce a current. If alternator charging the car battery, the lamp will turn off.

From the experiment, the motor needs to run with minimum frequency of 30 Hz so the alternator can charge the battery, indicated by having lamp indicator completely off, hence the data acquired are 30, 35, 40, 45, and 50Hz, and this data acquisition steps are the same as before, as shown on flowchart Figure 5.

3.2.1 Data Analytics of AC System with Additional Alternator on Blower Fan Speed 1

Using the same step and data acquisition set without alternator, acquiring this data start with blower fan speed on 1, shown on Figure 36 to Figure 40. The difference is when the inverter turned on, alternator also driven by electric motor to generate power into car battery, shown on graphs hiking up first, then going lower, until it's going back up again when AC unit turned on. Same after turning AC unit off, inverter still supplying power to spin the motor, but this time also spinning disengaged compressor and alternator.

The electric motor available was only meant to drive the AC system, adding alternator means bigger load to be driven with electric motor. In order to achieve this, electric motor pushed to its limit, sacrificing temperature drop to its lowest, but instead to reach the lowest surrounding temperature for human thermal comfort, around 16 $°C$ [19], [20].

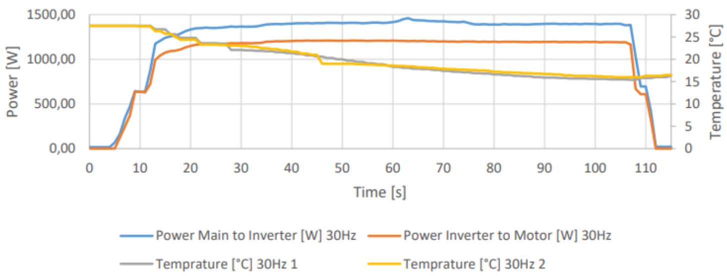

Figure 36. Power and Temperature Chart on Blower Speed 1 and 30Hz Frequency

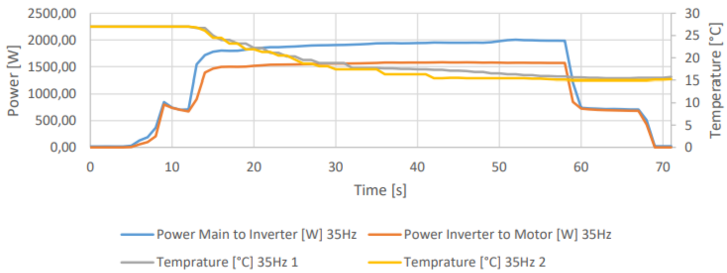

Figure 37. Power and Temperature Chart on Blower Speed 1 and 35Hz Frequency

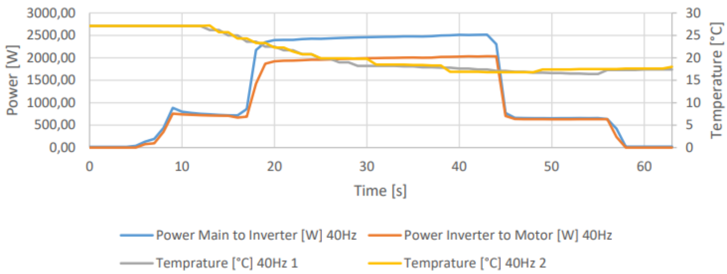

Figure 38. Power and Temperature Chart on Blower Speed 1 and 40Hz Frequency

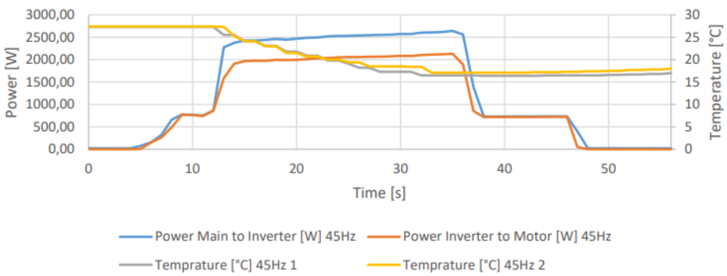

Figure 39. Power and Temperature Chart on Blower Speed 1 and 45Hz Frequency

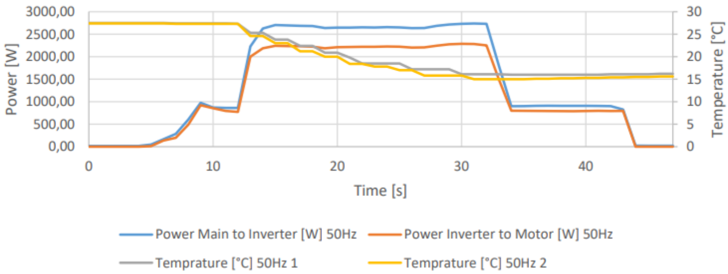

Figure 40. Power and Temperature Chart on Blower Speed 1 and 50Hz Frequency

As shown on Figure 40, the maximum power to drive this system are 2700 W on main to inverter, and 2200 W on inverter to motor. Energy also counted with Equation 1, shown on Figure 41 having best result at 50Hz with 16Wh energy usage.

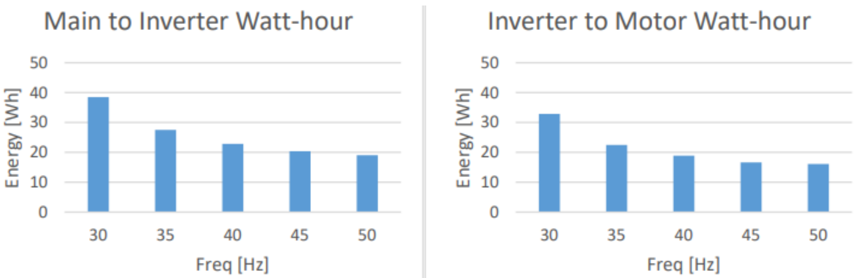

Figure 41. Energy Comparison on Each Frequency

Inverter efficiency also counted on this experiment on alternator addition, Figure 42 still show above 80% of efficiency similar result without alternator on every frequency, averaging 83% of efficiency.

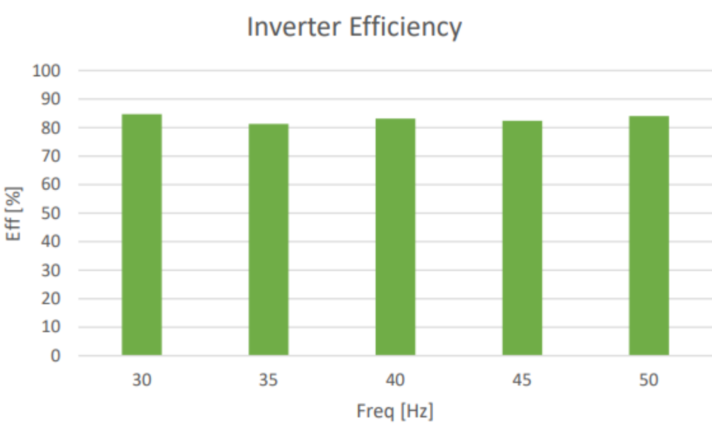

Figure 42. Inverter Efficiency Comparison on Different Frequency

Heat energy also counted using Equation 3 on every frequency, shown on Figure 43, with lower ΔT since the lowest temperature is around 16 $°C$, having average BTU rate of 1,44.

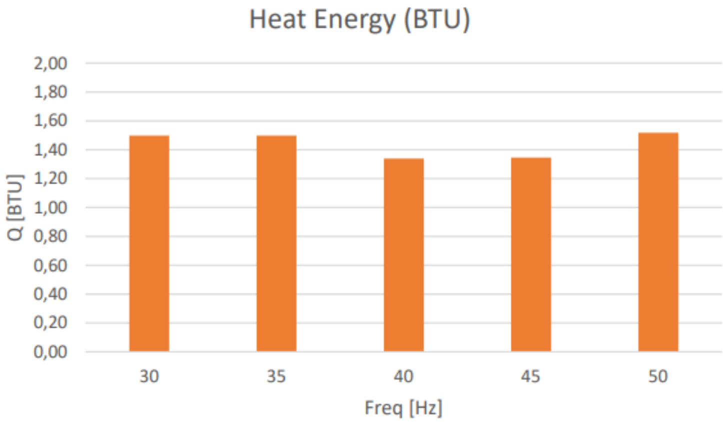

Figure 43. BTU Comparison on Each Frequency

3.2.2 Data Analytics of AC System with Additional Alternator on Blower Fan Speed 2

Data acquired for blower fan speed 2 with additional alternator are presented on Figure 44 to Figure 48.

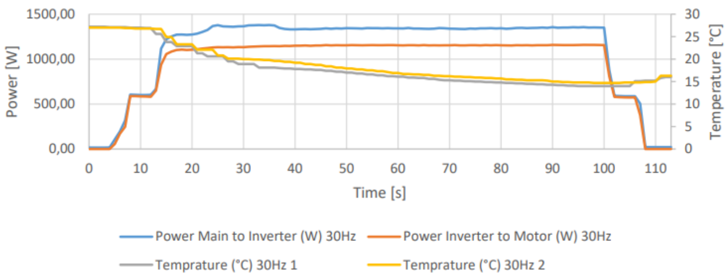

Figure 44. Power and Temperature Chart on Blower Speed 2 and 30Hz Frequency

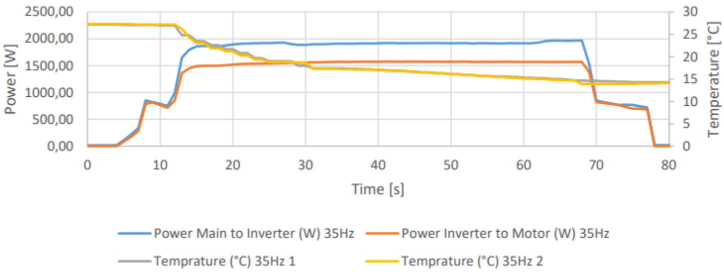

Figure 45. Power and Temperature Chart on Blower Speed 2 and 35Hz Frequency

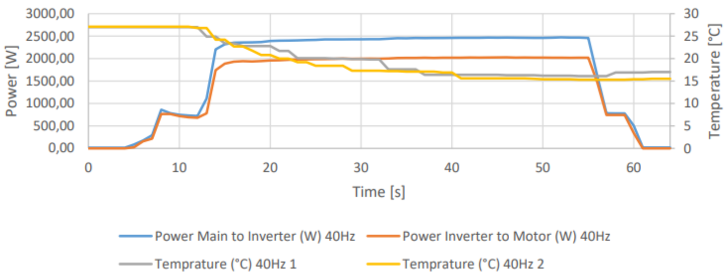

Figure 46. Power and Temperature Chart on Blower Speed 2 and 40Hz Frequency

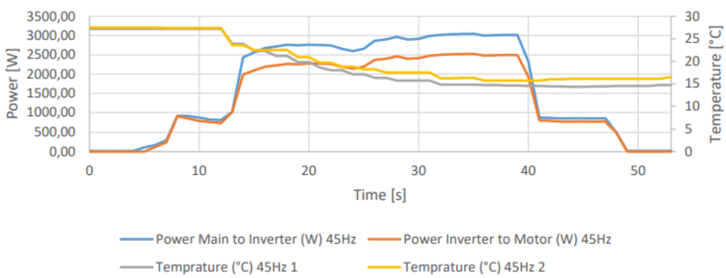

Figure 47. Power and Temperature Chart on Blower Speed 2 and 45Hz Frequency

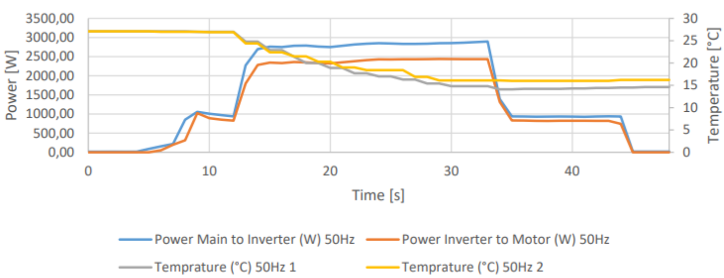

Figure 48. Power and Temperature Chart on Blower Speed 2 and 50Hz Frequency

Graphs displayed on Figure 44 to Figure 48 still prove the higher motor frequency is, the faster cabin got cooler, and the faster compressor got disengage, and the bigger power needed. This time with additional alternator on data acquired able to reach 3000 W on main to inverter, and 2500W on inverter to motor. The next step aforementioned, by using Equation 2 to calculate Energy on both data acquired, having the best result at 50Hz with 20Wh.

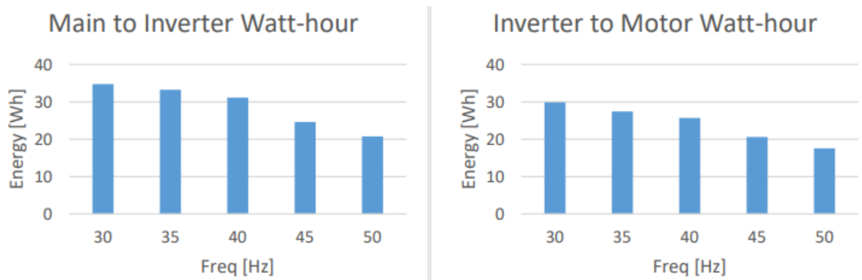

Figure 49. Energy Comparison on Each Frequency

Inverter efficiency for this run projected on Figure 50, with average of 84% efficiency.

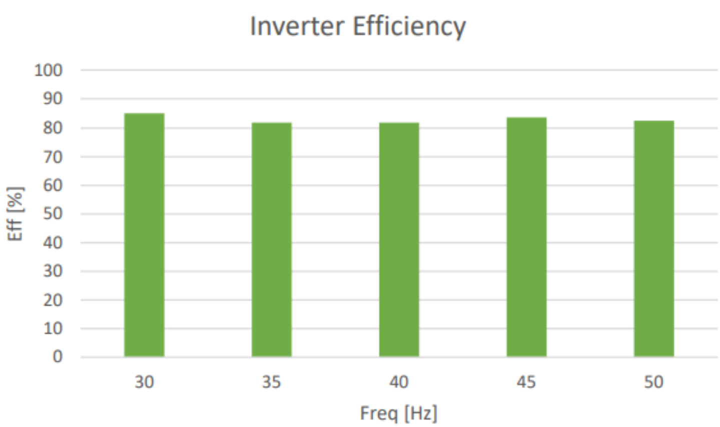

Figure 50. Inverter Efficiency Comparison on Different Frequency

Heat energy rate on each frequency run shown on Figure 51, averaging 1,57 BTU.

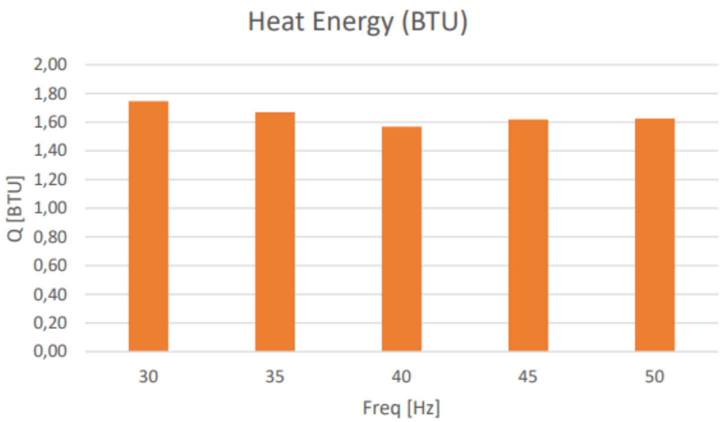

Figure 51. BTU Comparison on Each Frequency

3.2.3 *Data Analytics of AC System with Additional Alternator on Blower Fan Speed 3*

The final data acquired on this AC system with additional alternator are on this highest blower fan speed, presented on Figure 52 to Figure 55.

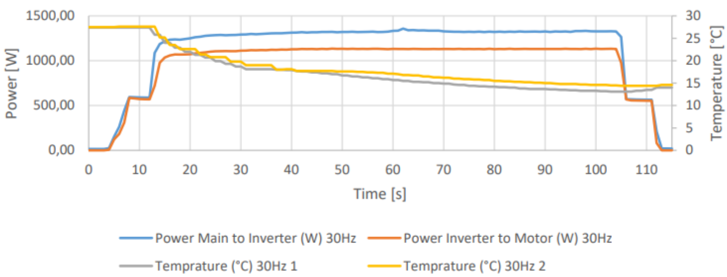

Figure 52. Power and Temperature Chart on Blower Speed 3 and 30Hz Frequency

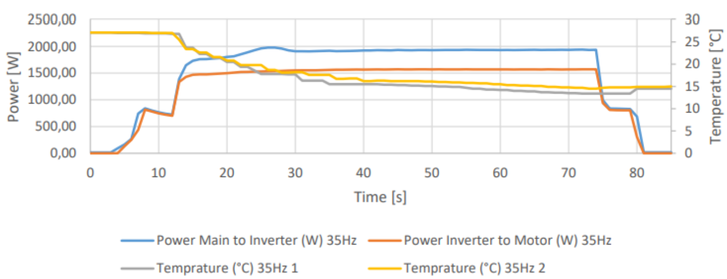

Figure 53. Power and Temperature Chart on Blower Speed 3 and 35Hz Frequency

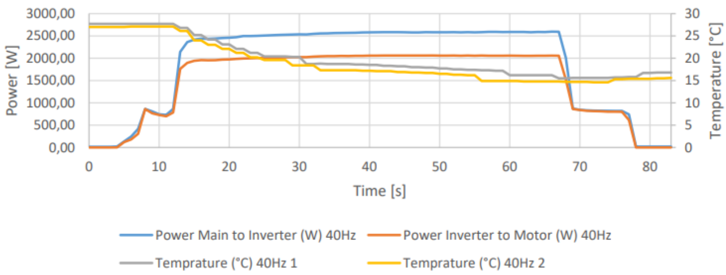

Figure 54. Power and Temperature Chart on Blower Speed 3 and 40Hz Frequency

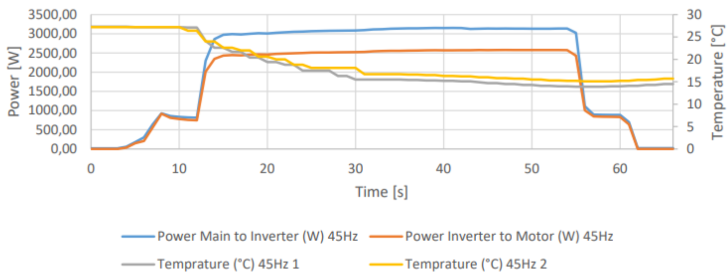

Figure 55. Power and Temperature Chart on Blower Speed 3 and 45Hz Frequency

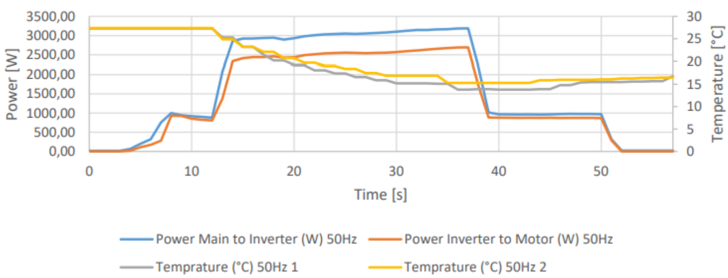

Figure 56. Power and Temperature Chart on Blower Speed 3 and 50Hz Frequency

The data, as shown in Figure 56, indicate that 50Hz is the best setting for this configuration, with 22Wh energy usage. Unlike the previous results for blower fan speeds 1 and 2, the energy projections do not progressively decrease with frequency, instead peaking at 40Hz. This behaviour suggests variations in the alternator's contribution to recharging the battery while maintaining stable voltage throughout the runs. Despite these variations, the system effectively supplies consistent power, reinforcing 50Hz as an optimal setting.

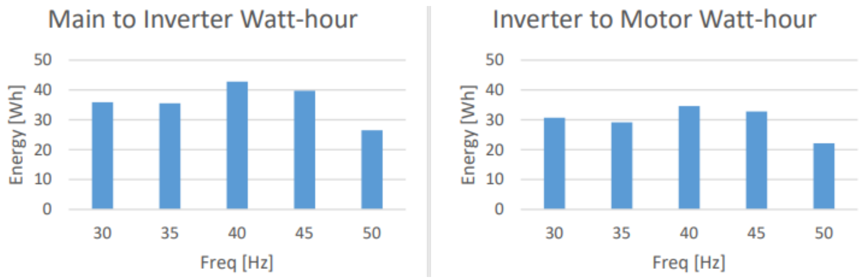

Figure 57. Energy Comparison on Each Frequency

Inverter efficiency on blower fan speed 3 can be seen on Figure 57, averaging 83% efficiency.

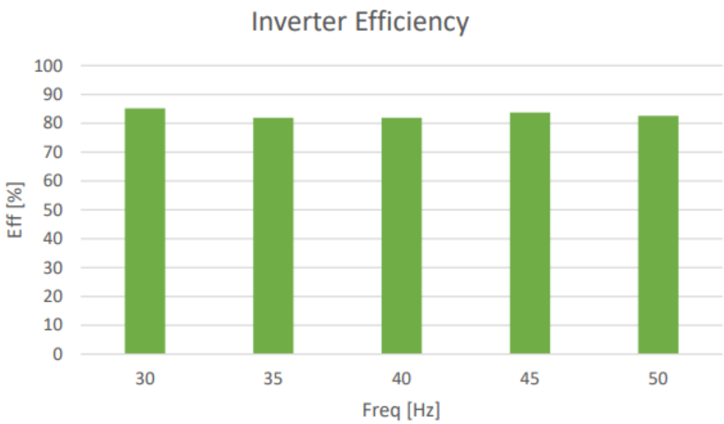

Figure 58. Inverter Efficiency Comparison on Different Frequency

Heat energy rate on settings blower fan speed 3 shown on Figure 58, achieving average of 1,65 BTU

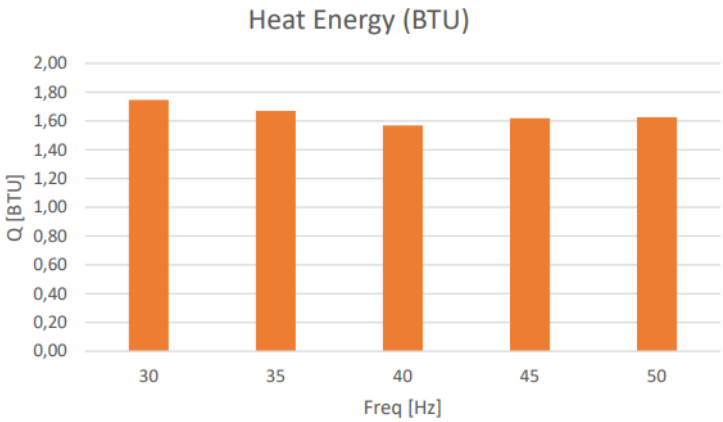

Figure 59. BTU Comparison on Each Frequency

4. Conclusion

The study demonstrates that traditional air conditioning systems from combustion engine cars can be effectively repurposed for electric vehicle conversions, minimizing waste and reducing costs associated with installing new systems. By modifying the compressor to be powered by an electric motor, the system's performance under varying inverter frequencies was analysed, revealing a balance between cooling efficiency and energy consumption. At higher inverter frequencies, faster cooling was achieved, but power usage also increased, highlighting the importance of identifying optimal frequency settings for efficient operation.

The addition of an alternator enabled the system to recharge the car battery, maintaining consistent performance over extended operations. This integration demonstrated the practicality of reusing not only the AC system but also other components like alternators to create a more sustainable conversion process. Furthermore, the use of a larger electric motor could enhance overall system performance by accommodating higher loads with improved efficiency.

Future studies could also explore integrating additional electrical systems, such as power steering, lighting system, or audio system into the alternator-powered setup, taking advantage of the enhanced battery stability. While this research demonstrates the feasibility of repurposing traditional AC systems for EVs, it also highlights broader opportunities for system optimization and opportunities for continued exploration for car conversion program.

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