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Part-Load Simulation and Energy Recovery Evaluation of an Electrically Turbocharged Engine Low Engine Speeds

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Abstract – *Hybridization has become a crucial part of engine development for automotive manufacturers nowadays to produce efficient engines and electric turbochargers have become the center-piece of that development to cut carbon emissions. In this paper, we simulate an electrically turbocharged engine under part-load using a 1-D engine simulation software to estimate the amount of energy that can be recovered at different engine loads in a typical passenger vehicle. A conventional turbocharged engine and an electric turbocharged engine are first simulated under steady part load conditions with fixed target Brake Torque (Nm). Then the electric turbocharged engine is simulated to run at points between 1,000-2,000 rpm engine range to determine the amount of power recovered at low engine speed. From this study, the BSFC increases by 1.3% at 50% engine load at 4,000 rpm in the electrically turbocharged engine over conventional turbocharged engine whereas at 5,000 rpm it decreases by 2.4% at 75% engine load. A maximum of 3.22 kW was able to be recovered at 5,000 rpm 50% load and 1.5kW at low engine speeds.*

Keywords: Electric turbocharger, 1-D simulation, energy recovery, part-load simulation

1.0 INTRODUCTION

Since the turn of the century, authorities have been more robust in their bid to cut carbon emissions and they have identified passenger vehicles as a big contributor to the carbon released into the atmosphere. The Euro 6 emission standards reflect the commitment by legislators to preserve the environment (European Parliament & Council of the European Union, 2007). These strict standards have forced automotive manufacturers to find innovative solutions to make their engines run on lower emissions (Abas et al., 2017).

For the past two decades, turbochargers have been the go technology for carmakers in making their engines efficient (Salim et al., 2017). Turbochargers basically work on the principle of increasing the volumetric efficiency by compressing waste hot exhaust gases in the intake manifold and running it through a compressor, therefore, allowing pressurized air into the combustion chamber of the engine (Noor et al., 2014). The time delay for the turbine to spool and for the compressed air to enter the combustion chamber during acceleration causes the driving performance to be sluggish at times.

Turbochargers can sustain damage and become less efficient when they overspeed the maximum speed limit. A wastegate solves this issue but causes the loss of waste heat energy to the surroundings and therefore never fully recovering most of the energy from the exhaust manifold (Winterbone et al., 1977). Dimitriou et al. (2017) study on controlling load by using a motor-generator to the turbocharger essentially show that the motor-generator in an electric turbocharger can replace the wastegate and recover energy besides reducing transient response by 90%. Wei et al. (2010) found that the placement of the motor-generator parallel to the turbocharger increases its efficiency when compared to other types of electric turbochargers.

Alshammari et al. (2019) found that there is an overall net reduction in BSFC of 0.53% and 1.45% when the motors of 1kW and 5 kW respectively are used to assist the turbocharger. Raspopović et al. (2018) discovered that the electrically turbocharged engine has better performance and efficiency compared to a conventional turbocharger. Simplicity in electric turbocharger design also has fewer exergy losses as discovered by Muhammad et al. (2018) when comparing exergy availability and losses between Organic Rankine Cycle and Electric Turbo-Compounding. The performance of the electric turbocharger is also influenced by using different types of motors. The reliability of the hybrid turbocharger improves when a brushless DC motor is used as found by Bingyong et al. (Gou et al., 2015). The compressors in the turbochargers can be electrically driven by High-Speed Synchronous Motors as done by Novák et al. (2009).

In this paper, a part-load simulation is carried out on a conventional turbocharged engine and an electrical turbocharged engine to determine the engine performance and energy recovery at different engine loads. Next, a smaller motor is used to simulate the electric turbocharger to determine the amount of energy that can be recovered at low engine speeds.

2.0 METHODOLOGY

For this study, the main scope of this paper is to run a part-load simulation to determine the engine performance and energy recovery at different engine loads. The other scope is to determine whether energy can be recovered at low engine speed and how much that can be recovered. A 2.0 litre SI turbocharged engine was used as a template for this study. The engine specification for this study is given found in Table 1.

The conventional turbocharged engine produces a peak Brake Power of 156.2kW at 5,000 RPM and 298 Nm at 3,000-5,000 RPM. For the electrical turbocharger, the conventional turbocharged engine was used, and certain modifications were made to convert the turbocharger unit into an electrical turbocharger. This was done with the aim of making sure both engines have the same peak Brake Power and Brake Torque. The turboshaft is separated so that a motor can be connected to the turbine and another to the compressor. The motor connected to the turbine acts as a generator. It recovers energy and stores it in the battery as electrical energy. The motor on the compressor assists in the compression of air to the intake manifold. The wastegate was removed with the generator, which is attached to the turbine preventing the turbine from over-speeding at high engine speeds. Figure 1 shows the setup of the electrical turbocharger with both the motors and battery.

Table 1: Engine specification for this study

Specification	2.0-litre turbocharged engine
Engine type	4-stroke Spark Ignition
Induction system	Turbocharged
Fuel delivery	Direct injection
Compression ratio	9.5
Bore x stroke	86mm x 86.07mm
Capacity	2.0 litre
Maximum power	156.2 kW (209 hp) @ 5,000 RPM
Maximum Torque	298 Nm @ 3,000-5,000 RPM

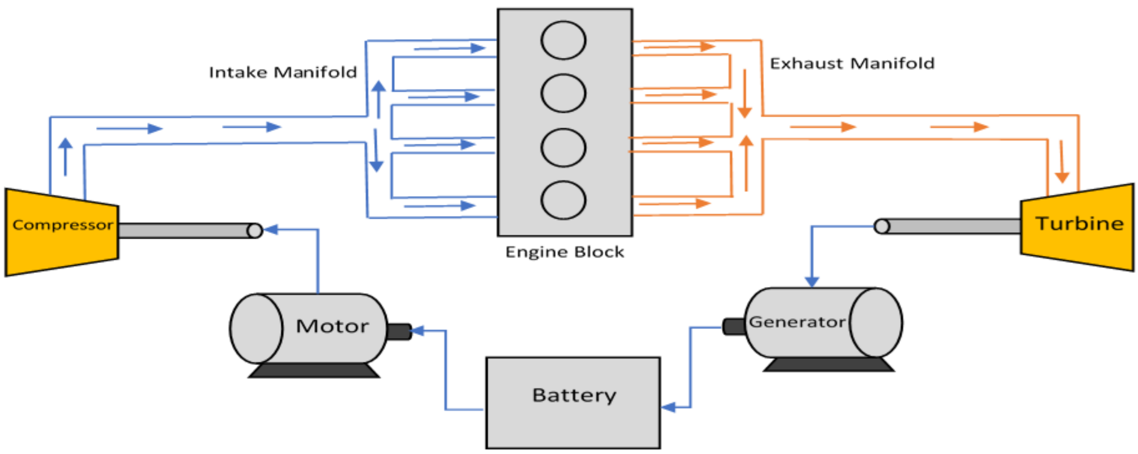

Figure 1: The setup of the electrical turbocharger system

The electric motor specification used to assist the compressor is a BorgWarner 23 kW motor. The generator used at the turbine is an 11.8-kW motor based on the model from e+a Elektromaschinen und Antriebe AG. The separation of the turboshaft enables the flexibility to use two different motor specifications as both the turbine and the compressor runs at different speeds and can be controlled by the motors used. The more powerful motor was used at the turbine as more power might be needed at certain instants during a drive cycle. The angular motion equation was used to calculate the amount of power produced by the generator as the motor is an angular moving device. Eq. (1) shows how to calculate the power produced by the motor (P) which is by multiplying the torque (T) produced by the motor which is obtained from the torque map with the angular velocity (ω) of the motor.

$$P = T\omega \tag{1}$$

The conventional and electrical turbocharger was first to run at full load (100%) to verify that both produce the same Brake Power and Brake Torque. Figure 2 shows the comparison between Brake Torque and Brake Power produced by the conventional turbocharged engine and electrical turbocharged engine.

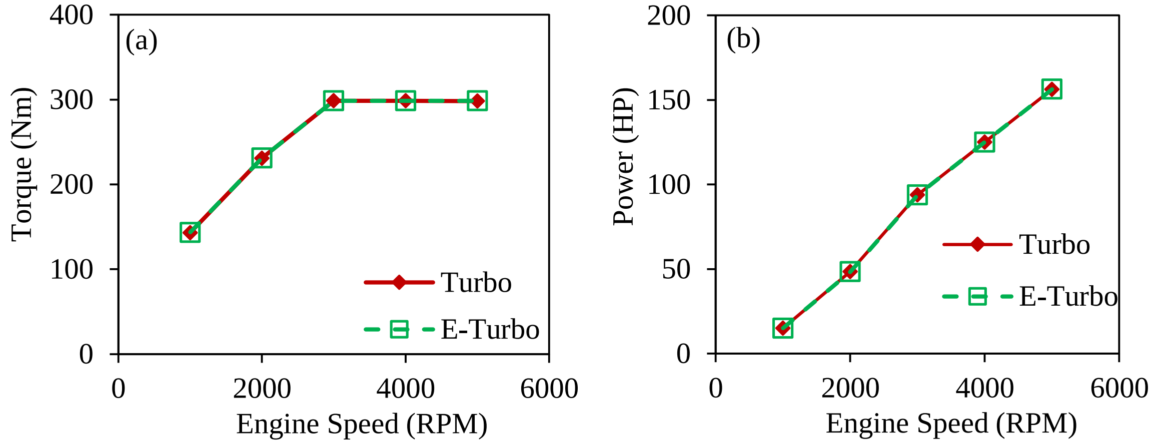

Figure 2: Engine Performance comparison between the conventional turbocharger and electrical turbocharged engines: (a) Brake Torque; (b) Brake Power

Based on the graphs in Figure 2(a) and Figure 2(b), both engines produce similar output in terms of Brake Power and Brake Torque. Therefore, this validates that both the engines have the same engine performance. Next, both the conventional turbocharged engine and electrical turbocharged engine were both runs at different torque load of 50% and 75% of the maximum brake torque. The engine performance and energy recovery of this part-load simulation are discussed in the result section. After the part-load simulation, the motor at the turbine is changed to a smaller 5.03 kW motor from e+a Elektromaschinen und Antriebe AG so that energy can be recovered at low engine speeds of 1,000-2,000 RPM. The energy recovered from the low engine speed simulation is discussed in the results section. Figure 3 shows the part-load points that were used to simulate the different torque outputs of the engine at the various engine speeds.

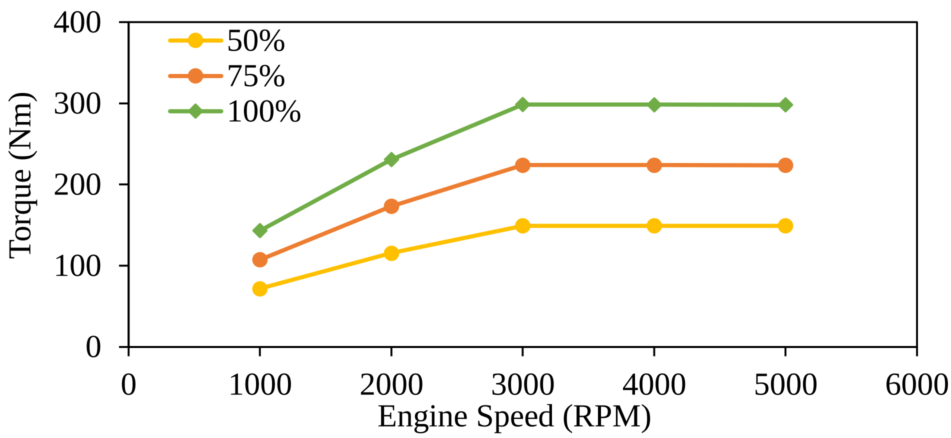

Figure 3: Part-load brake torque points at various engine speeds

3.0 RESULTS AND DISCUSSION

Figure 4 shows the energy recovered by the electric turbocharged engine at different engine loads. It can be observed that energy is only recovered at high loads or high engine speeds or both. 3.22kW is recovered at 5,000 rpm 50% load, 0.96kW at 4,000 rpm 75% load and 3.17kW at 3,000 rpm 100% load. Less power was recovered at 5,000 rpm due to the smaller motor used to recover energy at the turbine. By using a suitable motor, we can recover energy at low engine speeds or high engine speeds in accordance with the type of vehicle it is used. The system can be optimised by using a smaller motor so that energy can be recovered as a typical driving cycle for a passenger vehicle is only between 1,000-3,000 rpm.

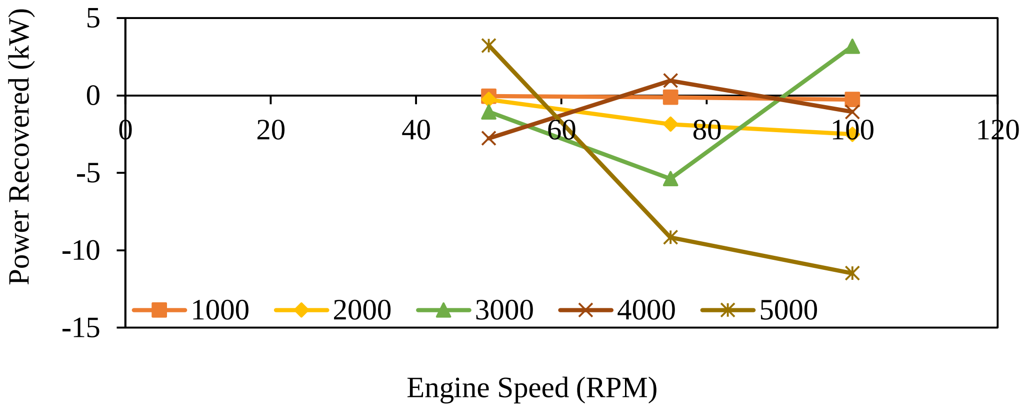

Figure 4: Power recovered at different engine loads

Figure 5 shows the energy that is recovered by the electric turbocharger at low engine speeds. A maximum of 1.5kW of energy was able to be recovered at 2,000 rpm. The overall trend shows that the electric turbocharger can recover energy from 1,600 rpm onwards. This is possible with the use of the small 5.06 kW motor rather than the 11.8kW used for the part-load simulation.

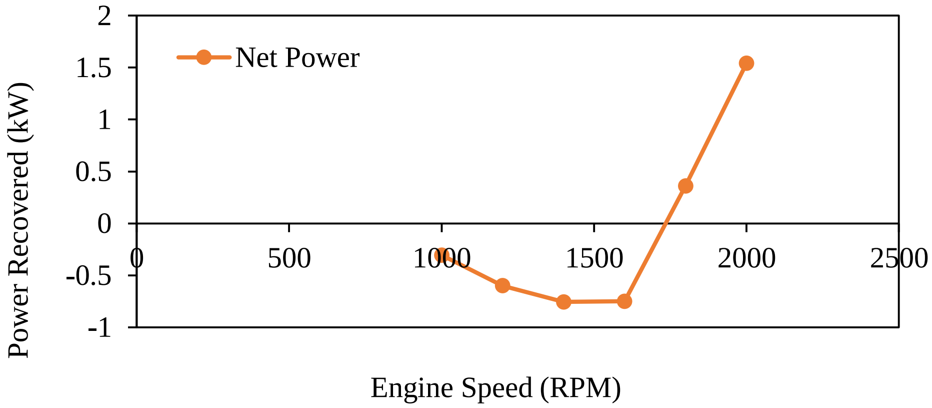

Figure 5: Power recovered at low engine speed simulation

Figure 6(a) and 6(b) shows the BSFC comparison at 4,000 & 5,000 RPM between both the conventional and electric turbocharged engine at different engine loads. At 4,000 rpm, the BSFC increases by 1.3% at 50% engine load in the electrical turbocharged engine over the conventional turbocharged engine. An increase in back pressure build-up at the exhaust manifold causes the BSFC increase. At 5,000 rpm, the BSFC decreases by 2.4% at 75% engine load. A decrease in back pressure build-up at the exhaust manifold causes the BSFC to decrease. Back pressure is the pressure at the manifold of the exhaust turbine and the back pressure for this simulation was measured from the pressure at the exhaust manifold before the turbine.

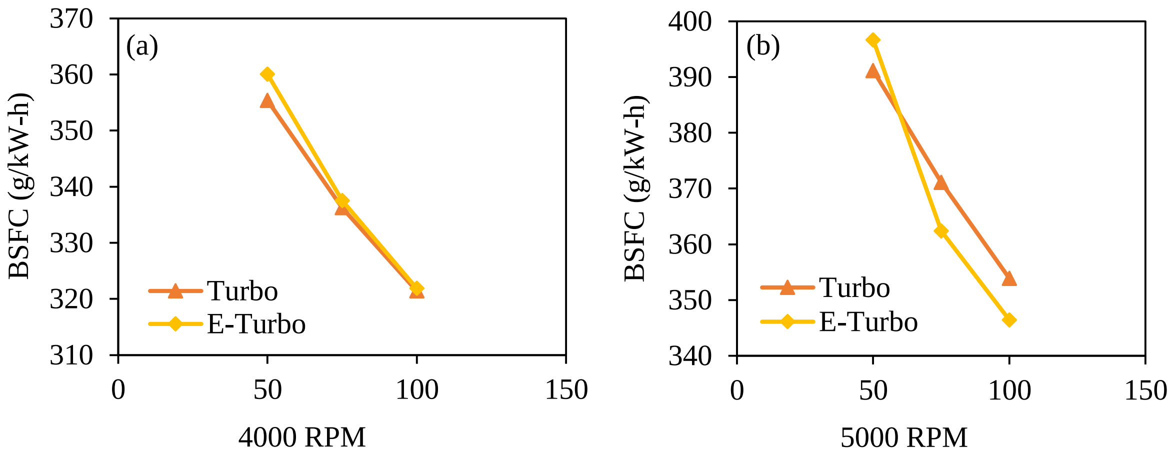

Figure 6: BSFC data comparison between the conventional turbocharged and electrical turbocharged engines at part-load simulation: (a) 4,000 rpm; (b) 5,000 rpm

The exhaust pressure comparison at 4,000 & 5,000 rpm between the conventional and electrical turbochargers at different engine loads is shown in Figure 7(a) and Figure 7(b). At 4,000 rpm, the exhaust pressure increases by 10.1% at 50% engine load in the electrical turbocharged engine over the conventional turbocharged engine. At 5,000 rpm, the exhaust pressure decreases by 28.5% at 75% engine load. Both the figures prove that the increase or decrease of BSFC is caused by the changes in back pressure.

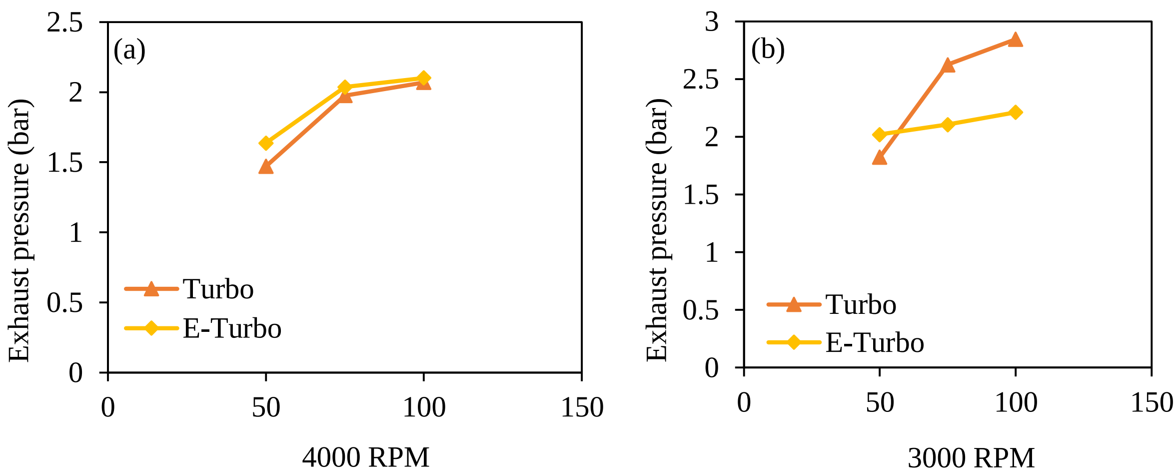

Figure 7: Exhaust pressure data comparison between the conventional turbocharged and electrical turbocharged engines at part-load simulation: (a) 4,000 rpm; (b) 5,000 rpm

4.0 CONCLUSION

The part-load simulation has helped determine specific points where energy is recovered. 3.22 kW was able to be recovered at 5,000 rpm 50% load. This study has also shown that the motor is a very crucial part of the electric turbocharger. An optimal motor-generator would enable the system to recover more energy efficiently and open new possibilities. The part-load simulation also identified various points where the changes in back pressure influence the BSFC of the engine. Lastly, the simulation where a smaller motor was used at low engine speed was able to recover 1.5kW at 2,000 rpm.

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REFERENCES

Abas, M. A., Wan Salim, W. S., Ismail, M. I., Rajoo, S., & Martinez-Botas, R. (2017). Fuel consumption evaluation of SI engine using start-stop technology. Journal of Mechanical Engineering and Sciences, 11(4), 2967–2978.

Noor, A. M., Puteh, R. C., & Rajoo, S. (2014). Waste heat recovery technologies in turbocharged automotive engine – A review. Journal of Modern Science and Technology, 2(1), 108-119.

Alshammari, M., Xypolitas, N., & Pesyridis, A. (2019). Modelling of electrically-assisted turbocharger compressor performance. Energies, 12(6), 975.

Dimitriou, P., Burke, R., Zhang, Q., Copeland, C., & Stoffels, H. (2017). Electric turbocharging for energy regeneration and increased efficiency at real driving conditions. Applied Sciences, 7(4), 350.

European Parliament, & Council of the European Union (2007). Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information. Official Journal of the European Union, L171(December 2006), 1–16.

Gou, B., Yang, Y., & Guo, H. (2015). Design on electric supercharger controller based on brushless DC motor. In 2015 International Power, Electronics and Materials Engineering Conference (pp. 758-761). Atlantis Press.

Raspopović, N., Dorić, J., Grujić, I., & Nikolić, N. (2018). Analysis of hybrid turbocharger in motor vehicle IC Engine. International Congress Motor Vehicle & Motors 2018, Kragujevac, Serbia.

Muhammad, M. H. M., Mamat, A. M. I., & Salim, W. S. I. W. (2018). Exergy analysis of organic Rankine cycle and electric turbo compounding for waste heat recovery. International Journal of Engineering & Technology, 7(3.11), 152-156.

Novák, L., Novák, J., & Novák, M. (2009). Electrically-driven compressors on turbocharged engines with high-speed synchronous motors. In 2009 8th International Symposium on Advanced Electromechanical Motion Systems and Electric Drives Joint Symposium.

Salim, W. S. I. W., Mahdi, A. A. M., Ismail, M. I., Abas, M. A., Martinez-Botas, R. F., & Rajoo, S. (2017). Benefits of spark-ignition engine fuel-saving technologies under transient part load operations. Journal of Mechanical Engineering and Sciences, 11(4), 2289–4659.

Wei, W., Zhuge, W., Zhang, Y., & He, Y. (2010). Comparative study on electric turbo-compounding systems for gasoline engine exhaust energy recovery. Proceedings of the ASME Turbo Expo, 5, 531–539.

Winterbone, D. E., Benson, R. S., Mortimer, A. G., Kenyon, P., & Stotter, A. (1977). Transient response of turbocharged diesel engines. SAE Technical Papers.