# Electric Forced Induction System for Downsized Internal Combustion Engines and Hybrid Electric Vehicles

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***Abstract***- **Forced induction is the process of delivering compressed air to the intake of an internal combustion engine. A forced induction engine uses a gas compressor to increase the pressure, temperature and density of the air. An engine without forced induction is considered a naturally aspirated engine. The electrification of forced induction system, called electric forced induction system (EFIS), has emerged as a feasible solution and it also possesses numerous benefits depending on its topologies. This paper provides a comprehensive study on EFIS by investigating system level topologies, performance, various types of high-speed machines, power electronics, and control techniques.**

**Index Terms- electrically assisted turbocharger; electric supercharger; electric turbocharger; Electrically split turbocharger, Turbocharger with an additional electrically driven compressor – up and downstream.**

## I. INTRODUCTION

The use of an internal combustion engine (ICE) using liquid-transportation fuel will presumably continue to hold a major role over the next few decades. However, there are still significant challenges for improving fuel efficiency and reducing emissions considering the rapid growth of environmental concerns. Many solutions have been used in the past to improve the fuel efficiency, including turbocharging and hybridization. Besides, driveability is another important measure of performance which assesses vehicle's speed and acceleration characteristics. It also quantifies driving comfort in the form of frequency of engine onoffs, frequency of gear shifts etc. While the passenger vehicles should be able to meet the basic acceleration demands in a driving cycle with minimal fuel requirements and sometimes also operate in sportive mode, acceleration performance finds more importance over fuel consumption in racing sports. The most common way to improve the driving performance of a turbocharged engine is by means of an electrical assist which ensures both extra power and high acceleration. Engine downsizing is one of the key solutions used by carmakers to reduce vehicle fuel consumption," explains automotive supplier Valeo in a statement. "However, to maintain high performance with a downsized engine, car manufacturers generally use an exhaust-driven turbocharger, which comes with a delayed boost response known as turbo lag." That slow response has been plaguing turbocharged cars for years and is a common complaint. Things like twin-scroll turbochargers or smaller turbos are used as a means to combat lag, but it's still not perfect. Simply put, it's hard to make a turbocharged engine deliver the immediate response of a naturally aspirated one. Among these recent technologies, the engine downsizing with forced induction system (FIS) such as a turbo charger or an electrified turbocharger is gaining popularity as a viable solution, which has not yet been practically implemented in passenger or light-duty vehicles. Compared to a conventional non-electric forced induction system (NFIS), the newly introduced electric forced induction system (EFIS) has several benefits including:

- improved transient response (reduced turbo lag)
- engine downsizing
- high fuel economy
- improved engine output power
- low carbon emission
- energy regenerative capability

## II. ELECTRIC FORCED INDUCTION SYSTEM (EFIS)

The electrification of NFIS can be realized in 5 different topologies as shown in Fig. 1 (a), (b), (c), (d) and (e). Since the main advantages of EFIS are to improve transient performance and minimize the lagging effect, roots and twin screw superchargers, which have relatively high boost performance in low engine RPM are not feasible for the electrification . Nevertheless, the centrifugal supercharger can be electrified and the topology is equivalent to the electric turbocharger as illustrated in Fig.1 (b). The characteristics, advantages, and disadvantages are summarized in Table I. In order to improve the transient response of the conventional turbocharger using an electric machine, the torque/inertia ratio (or angular acceleration, α) of EFIS must be higher than that of the conventional NFIS as shown in:

$$\frac{T_{EFIS\_net}}{J_{EFIS}} > \frac{T_{NFIS\_net}}{J_{NFIS}}$$

Minimizing the inertia of the overall system and maximizing output torque are the challenges in EFIS and 5 different topologies are characterized based on this equation.

A. Electrically assisted turbocharger (EAT)

Providing assistance to the turbocharger in turbocharged engines has long been an option that engine designers have utilized to address two undesirable characteristics of many turbocharged engines—namely low boost pressure at low engine speeds and turbocharger lag. This assistance can take one of several forms. Additional power can be supplied directly to the turbocharger shaft from an electric or hydraulic motor or even the engine itself. Alternatively, an additional compressor, either a supercharger or even a smaller turbocharger, can be used to provide boost when the primary turbocharger is unable to do so. Helhmoltz resonators and pulse chargers have also been proposed for providing this assistance.

Electric assisted turbochargers are turbochargers employing a coaxial electric motor to overcome the time lag of the exhaust gas driven turbine. The electric motor supports the exhaust gas driven turbine at low-end revolutions to compress enough air into engine's intake, while it can be configured as an alternator to extract energy from the exhaust gas driven turbine at high-end revs, which would otherwise need be bypassed via waste gate and eventually replacing the current mechanically driven alternator. Special consideration need be given to the coaxial electric motor operating in proximity of a hot turbine at very high rotational speed (up to 100000 rpm).

$$\frac{T_{T\_EAT} + T_{EM\_EAT} - \left|T_{C\_EAT}\right| - \left|T_{Mech\_load\_EAT}\right|}{J_{TC+EM}} > \frac{T_{T\_conv} - \left|T_{C\_conv}\right| - \left|T_{Mech\_load\_conv}\right|}{J_{TC\_conv}}$$

where

*TT_EAT* EAT turbine output torque,
*TEM_EAT* EAT electric machine output torque,
*TC_EAT* EAT compressor load torque,
*TMech_load_EAT* EAT mechanical load torque,
*JTC+EM* turbine, compressor and electric machine inertia,
*TT_conv* conventional turbocharger turbine output torque,
*TC_ conv* conventional turbocharger compressor load torque,
*TMech_load_onv* conventional turbocharger mechanical load torque,
*JTC_conv* conventional turbocharger inertia.

A high-speed electric machine is interconnected between the turbine and the compressor. When the engine speed is low, the electric machine functions as a motor providing additional torque to the compressor generating higher boost pressure with a faster transient response. When the engine speed is high, the electric machine generates power, which can be transmitted to energy storage. It can also prevent the turbine to exceed its speed limitation.

An additional advantage of all electrically assisted topologies lies in the fact that during a limited period of time consumption of the electric energy might significantly exceed its production due to availability of electric storage devices. This means that during those periods electric energy might be added to the air supply components while simultaneously electric energy is not produced, e.g. by devices powered by the engine shaft, thus increasing effective engine power output.

It should also be considered that the full power output of the EM could not always be used during transient operation of the engine utilizing electrically assisted turbocharger, since compressor surge has to be avoided. This is also the main limitation for increasing steady-state engine power output at low engine speeds, while increasing steady-state engine power output at mid- to high-engine speeds is mainly limited by the maximum in-cylinder pressure, maximum exhaust gas temperature, maximum temperatures of liner, piston, cylinder head and valves as well as maximum turbocharger speed.

Typically, the additional rotor inertia of the electric machine should be limited from 1/3 to a maximum 1/2 of the mass moment inertia of the turbocharger to efficiently assist the turbocharger [13]. The angular acceleration of the free electric machine should be an order of magnitude larger than that of the baseline turbocharger to significantly improve the transient response. The main challenge of this topology is to minimize the high-temperature effect on the electric machine, especially when the machine is placed inside the turbocharger. For instance, BMW utilized clutches to connect and disconnect the electric machine to the shaft of the turbocharger so that the machine can be placed outside of the turbocharger.

Applications

- Torque Curve Shaping
- Transient Response Improvement
- Alternative to Hybrid Drivetrains
- Engine Efficiency Improvements
- Particulate Emission Control

Electric turbocharger / supercharger (ET).

An electric supercharger is a specific type of supercharger that uses an electrically powered forced-air system that contains an electric motor to pressurize the intake air. By pressurizing the air available to the engine intake system, the air becomes more dense, and is matched with more fuel, producing the increased horsepower to the wheels. An electric supercharger, if supplied by common stock electric accumulators, runs independent of the engine to which it provides its boost. However, electrical energy consumed is often higher than what a production-line generator (e.g. alternator) of the engine can supply. Larger alternators are therefore fitted to recharge accumulators during the engine run.

The efficiency of an electric supercharger is curbed by several energy conversion losses (alternator for charging), damp energy while charging the accumulators and the compressor providing boost. The losses are in general higher than direct kinematic linkage of intake air compressor to engine crankshaft. If the vehicle implements kinetic energy recovery, then the battery can be charged on otherwise wasted energy.

$$\frac{T_{EM\_ET} - \left|T_{C\_ET}\right| - \left|T_{Mech\_load\_ET}\right|}{J_{C+EM}} > \frac{T_{T\_conv} - \left|T_{C\_conv}\right| - \left|T_{Mech\_load\_conv}\right|}{J_{TC\_conv}}$$

where

*TEM_ET* ET electric machine output torque,
*TC_ET* ET compressor load torque,
*TMech_load_ET* -ET mechanical load torque,
*JC+EM* Compressor and electric machine inertia.

The electric turbocharger (ET) is illustrated in Fig. 1 (b).

The energy for driving the compressor is solely provided from electric energy storage so that it has more flexibility in terms of control. In addition, the compressor can be operated in its optimal operating point ensuring high efficiency. The electric components are required having high power output compared to other topologies. This topology does not have the capability of energy generation itself but the regenerative braking system or integrated starter generator (ISG) can be combined to provide electrical energy to the energy storage . The torque /inertia ratio can be fulfilled if an electric machine with high power density with low inertia is utilized.

C. ELECTRICALLY SPLIT TURBOCHARGER (EST)

The third topology is called electrically split turbocharger (EST) as shown in Fig. 1 (c). In this topology, the mechanical energy from exhaust gas is not directly delivered to the compressor, but converted to electrical energy initially using a generator. The stored energy is utilized to drive the compressor for boosting. The advantages of this topology are almost equal to the electric turbocharger, but it has a capability of energy generation from the exhaust gas. the EM in electrically split turbocharger is more powerful compared to the EM in electrically assisted turbocharger.

During specific drive cycles the electric energy consumed by the electric motor driving the compressor might exceed the electric energy produced by the turbine driven generator. In such cases additional electric energy should be produced by the generator/alternator powered by the engine shaft.

Due to the possibility of controlling the air mass flow more accurately the electrically split turbocharger bears potential to improve fuel economy of diesel engines, since compressor power is not wasted to provide very high air-fuel ratios. However, this topology might bring more advantages if fitted to a spark-ignition engine by reducing the throttle losses.

In the analyzed case a smaller turbine was utilized in the electrically split turbocharger. It can be observed in Figure 4g that VGT position of the baseline engine does not exceed 0.6 indicating that the turbine is relatively large. Moreover, decreasing turbine size does not lead to the risk of crossing the compressor's surge line, since the compressor of the electrically split turbocharger can spin at speeds different from those of the turbine. Thereby it is made possible that at low engine speeds the turbine produces sufficient electric energy to solely provide the compressor with the power required for supplying sufficient amount of air to retain relative air/fuel ratios similar to those of the baseline engine at equal fuelling (relative air/fuel ratio is equal to the ratio of actual in-cylinder air/fuel ratio divided by the stoichiometric air/fuel ratio). The characteristics of a smaller turbine were obtained by scaling original turbine by a diameter ratio of 0.9 according to the similarity analogy presented. The main advantages of this topology are the following:

- air supply could be controlled more independently and thus optimized with regards to power consumption and/or emissions and/or engine performance,
- the turbine could be operated in its optimal efficiency range considering thermodynamic parameters of the exhaust gasses,
- there is no need for fast turbine speed changes thus posing less compromises on the turbine performance with the aim to decrease its inertia,
- decoupling of the compressor and the turbine speeds enables efficient electric power supply while using electric machines featuring larger inertias than those of the turbo machinery,
- the EM drives only the compressor thus making possible faster boost pressure build-up.
- advanced material to produce compressor rotor might be applied resulting in its lower inertia, since it needs to be less heat resistant as it is not attached to the turbine.

There are two main disadvantages of this concept. First disadvantage is related to much larger losses associated with the energy transfer from the turbine to the compressor compared to the mechanical energy transfer between the two in a conventional TC. Second disadvantage arises from the necessity of using electric components with larger power outputs, since entire energy transfer from the exhaust gasses to the compressed fresh air is performed via the electric components. This results in higher mass and particularly in higher cost of the electric devices.

$$\frac{T_{EM\_EST} - \left|T_{C\_EST}\right| - \left|T_{Mech\_load\_EST}\right|}{J_{C+EM}} > \frac{T_{T\_conv} - \left|T_{C\_conv}\right| - \left|T_{Mech\_load\_conv}\right|}{J_{TC\_conv}}$$

where

TEM_EST EST electric machine output torque,
TC_EST EST compressor load torque,
TMech_load_EST EST mechanical load torque,
JC+EM compressor and electric machine inertia.

Splitting the turbine and the compressor is also beneficial in terms of installation so that the airflow path can be optimized. However, this topology requires high power rating electric motor and generator as well as inverters to satisfy torque/inertia ratio in, which will increase the overall system cost.

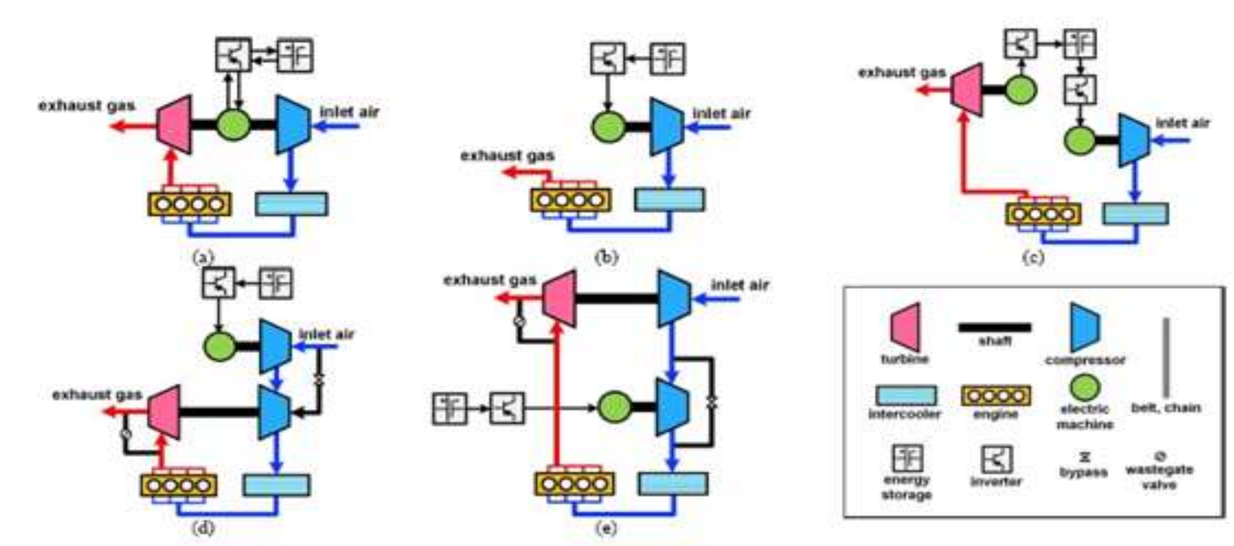


Fig. 1. Schematic layout of electric forced induction system (EFIS) topologies (black line (thin) – power flow, black line (thick) – air flow path withvalve, blue line – engine inlet air flow, red line – exhaust gas flow). (a) Electrically assisted turbocharger (EAT). (b) Electric turbocharger (ET). (c)Electrically split turbocharger (EST). (d) Turbocharger with an additional electrically driven compressor - upstream (TEDC). (e) Turbocharger with an additional electrically driven compressor - downstream (TEDC).

D. Turbocharger with an additional electrically driven
compressor – up and downstream (TEDC).

The last topology is the turbocharger with an additional electrically driven compressor (TEDC) as shown in Fig.1 (d) and (e). Depending on the location of the electrically driven compressor, TEDC can be classified into upstream and downstream TEDCs. In this topology, the electric machine operates independently from the engine exhaust gas driven turbine and the electrically driven compressor is designed to increase air pressure at low engine speed. Therefore, this topology significantly improves the transient response when the engine speed is low since the electric motor operation is not affected by the inertia of the turbine nor the shaft. However, the electric energy needs to be produced from ISG powered by the engine shaft or regenerative braking system.

The main advantages of this topology are the following:

- it is generally possible to attain very high pressure ratio across electrically driven compressor at low engine speeds, since electrically driven compressor is generally sized to increase boost pressure at lower engine speeds and thus features ample surge margin at low engine speeds,
- EM drives only compressor making possible faster boost pressure build-up,
- advanced material to produce compressor rotor might be applied resulting in its lower inertia, since it needs to be less heat resistant as it is not attached to a turbine. Due to above facts and due to the fact that both compressors are used to compress the air, turbocharger with an additional electrically driven compressor inherently offers large potential for transient response improvement if transient starts at low engine speed.

Transient response improvement compared to other turbocharging topologies is characterized by eq. (1), since this topology applies two compressors. Due to the above facts a turbocharger with an additional electrically driven compressor also offers larger potential for improving steady-state power output at low engine speeds while at high-engine speeds the electrically driven compressor could generally not be utilized due to its small mass flow range. The main disadvantage of this topology results from the fact that all electric energy used to power electrically driven compressor needs to be produced by a generator/alternator powered by the engine shaft. An electrically driven compressor is generally smaller compared to the turbocharger's compressor, since it is aimed to increase boost pressure at lower engine speeds while preserving ample surge margin. The characteristics of the smaller compressor were obtained by scaling original compressor by a diameter ratio of 0.86 according to the similarity analogy presented. In general, downstream TEDC has a faster transient response than upstream TEDC since the latter has a larger volume to pressurize. The other advantage is that it can be adopted with the minimal modification to the conventional automotive system with the turbocharger.

Table 1 THE COMPARISON OF ELECTRIC FORCED INDUCTION SYSTEM TOPOLOGIES

| TYPE | EAT | ET | EST | TEDC (UPSTREAM AND DOWNSTREAM) | |
|---|---|---|---|---|---|
| ENERGY SOURCE | Exhaust gas / Energy storage | Energy storage | Exhaust gas / Energy storage | Exhaust gas / Energy storage | |
| TEMPRATURE EFFECT | High | Low | Low | Low | |
| ELECTRIC TURBO COMPOUNDING | Yes | No | Yes | No | |
| ADVANTAGES | Compact size<br>- Low rating motor and inverter<br>- No wastegate valve | - Compact size<br>- No additional inertia<br>- Control flexibility<br>- Installation flexibility<br>- No backpressure | - No additional inertia<br>- Control flexibility<br>- Installation flexibility<br>- No wastegate valve | Upstream<br>- No additional inertia<br>- Low power motor and inverter<br>- Steady-state performance improvement | Downstream<br>- Fastest transient response<br>- Low power motor and inverter<br>- Steady-state performance improvement |
| DIS ADVANTAGES | - Additional cooling<br>- Additional shaft inertia | - High rating motor and inverter<br>- Low system efficiency | - High rating motor and inverter<br>- Extra space required<br>- Extra energy conversion loss | - Not the fastest transient response<br>- Extra space required<br>- Low system efficiency | - Extra space required<br>- Low system efficiency |

## II. CONCLUSIONS

Results of large variety of operating conditions reveal that no electrically assisted turbocharger topology could clearly be favoured in general. However, results provide sufficient insight to support selection of most suitable electrically assisted turbocharger topology based on the intended vehicle operation. Presented analyses reveal that all electrically assisted turbocharger topologies improve transient response of the engine and thus driveability of the vehicle. It has also been exposed that during a limited period of time. electrically assisted turbocharger topologies could improve steady-state torque output of the engine by retaining the fuelling, which is made possible by the availability of the energy stored in the electric storage devices. Results indicate that the engine utilizing turbocharger with an additional electrically driven compressor features the highest low speed torque output and the fastest transient response for transients starting at low engine speeds, since boost pressure build up-is not limited by the surge line.

The engine utilizing electrically assisted turbocharger improves transient engine performance, whereas it also posses the potential to increase high speed torque output during limited period of time. In the analyzed case, the engine utilizing electrically split turbocharger features similar transient response improvement compared to the engine utilizing electrically assisted turbocharger, since both improvements are limited by equal surge limit of the compressor. During a limited period of time it is also possible to increase steady-state power output by the utilization of the electrically split turbocharger. Furthermore, electrically split turbocharger topology features load point dependent trends in fuel economy improvement compared to the baseline engine. At the full load, fuel economy of the engine utilizing electrically split turbocharger is worse due to larger losses associated with the transport of the energy from the turbine to the compressor. However, at low loads this topology enables considerable fuel economy improvement by optimizing energy consumption of the compressor and thus improving gas exchange IMEP.

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